Water Balance of a Feedlot

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By

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ABSTRACT

The overall purpose of this study was to define the water balance of feedlot pens in a Saskatchewan cattle feeding operation for a one year period. Although the initial intention of the study was focused upon an active feedlot, cattle were removed from the pens in July 2003. Therefore, the year of analysis was conducted on the manured surface of an inactive feedlot. The water balance was also performed on a scraped soil surface, since manure is removed from the pens and spread on agricultural land, leaving the pen surfaces bare for a short period of time each year.

During the monitoring period (Sept. 2003 to Aug. 2004), 313 mm of precipitation was received at the feedlot, but only 84 mm of that total was received before June 2004. Winter precipitation was very low (33 mm) and there was no observed runoff from it. Runoff collection weirs in operation for only part of the summer recorded no runoff. The Green-Ampt and USDA SCS runoff models, as well as a snowmelt runoff equation, were used to predict runoff from both the manure pack, as well as the scraped soil surface.

Using manure and soil hydraulic parameters determined in the laboratory (from falling head permeameter measurements) and the field (from rainfall simulations), as well as incorporating the greatest 24 hour rainfall amounts and 30 minute intensities experienced at the feedlot, the USDA model found that 29 mm of runoff would occur from the scraped soil surface. Additionally, snowmelt runoff was estimated to be 19 mm for the winter precipitation received. Drainage beneath the 0.6 m soil depth was negligible and the top 0.6 m of soil experienced an increase in moisture of 54 mm. Finally, 211 mm was lost as evaporation.

For the manure pack, no runoff was predicted using the Green-Ampt and USDA SCS models and snowmelt runoff equation, which corresponded well to the lack of runoff measured both from the weir and rainfall simulations. Drainage beneath 0.6 m soil depth was negligible. Of the 313 mm of precipitation that fell during the study year, 42 mm was stored within the manure pack and the rest was lost as evaporation (271 mm).

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1. INTRODUCTION

1.1 Purpose

The purpose of this study is to define the hydrology of a prairie cattle feeding operation. The project evaluated the seasonal water balance of a set of pens at a cattle feedlot in Saskatchewan through determination of evaporation, drainage to groundwater, runoff, and changes in soil moisture storage. This overall water balance of a feedlot operation will help assess the potential for contamination in water pathways, such as drainage beneath the feedlot floor and runoff.

1.2 Relevance

Due to agricultural diversification beef feedlots in the prairies are undergoing rapid expansion and intensification. Feedlots represent a billion dollar industry for the prairies and their expansion has led to increased environmental concerns about siting and water contamination potential. Feedlot pens in the prairies are generally formed on compacted earthen floors and runoff is collected into earthen holding ponds. As the climate is cold and semi-arid (350 mm precipitation, 800-1000 mm potential evaporation) runoff is generally limited to spring snowmelt runoff and the occasional summer convective storm. Water tables in this region are generally deep (3 to 10 m) and recharge within agricultural cropped lands low (5 to 15 mm/yr). Evaluation of the water balance will help pinpoint possible routes and occurrences of contaminant outflow from the feedlot and provide a siting aid for regulatory purposes.

Safe, responsible development of the intensive livestock industry is important to the economic viability of the province of Saskatchewan. Over 2,300 approvals for intensive beef, hog, dairy and poultry operations have been issued since 1971. It is pertinent to do a water balance of a feedlot pen because it is important to know the volumes of water leaving the feedlot pens either via the groundwater and/or surface runoff.

Current provincial siting regulations require design capacity of holding ponds for at least 75 mm (3 inches) of runoff from the contributing area (Saskatchewan

Agriculture, Food and Rural Revitalization 2004). Many jurisdictions use the volume of a 1 in 25 year-24 hour rainfall event to determine the holding pond volume, which, for Saskatchewan, corresponds very closely to 75 mm. As it stands currently, it is uncertain whether this regulation is sufficient or overcompensates for the actual runoff from feedlot penning areas.

Gee and Hillel (1988) defined the soil water balance as D = P – Ea – ΔS – R, where groundwater recharge (D) is equal to precipitation (P) minus the actual evapotranspiration (Ea) minus the change in soil moisture storage (ΔS) minus runoff (R). Several other studies (Lane et al. 1983, Van der Velde 2005) have also utilized the soil water balance method to describe the hydrologic regime in agricultural watersheds, but there has been no research on water balances of feedlot pens done to date. In addition, several authors have used water balance models to determine the evaporation and seepage losses from lagoons and earthen manure storages (Parker et al. 1999, Ham 1999, and Ham and DeSutter 2000). While there is an entire body of research on water balances in feedlot holding ponds, there has been none on the feedlot pens themselves.

Many soil water balances have been conducted in semi-arid environments, but it has been pointed out by Allison et al. (1994) and Freeze and Cherry (1979), among others, that the balance is only as accurate as its measured components, such as precipitation and evapotranspiration. For example, Gee and Hillel (1988) stated that drainage calculated by the difference method from measurement of other water balance components, can be significantly affected by the accuracy of precipitation and actual evaporation measurements, which are often inaccurate by up to 10%.

There has also been very little research involving infiltration and runoff characteristics of a feedlot pen using a rainfall simulator. The use of a rainfall simulator is of great benefit because rainfall events in Saskatchewan are inconsistent and hard to predict. Thus, a rainfall simulator is useful because it can mimic natural rainfall and subsequently model characteristic infiltration and runoff conditions for a field plot. In addition, the measurements are convenient and results are easily compared between plots and sites. It can also simulate different storm intensities, different storm lengths, and provide a great number of simulations. This thesis work involved a water balance of a feedlot in Saskatchewan and used a Guelph Rainfall Simulator (GRS II) to generate infiltration and runoff curves.

1.3 Objectives

The thesis objective was to quantify the water balance of an inactive cattle feedlot pen, both with a manured surface, as well as a scraped soil surface (which would normally occur when the pens are cleaned). Although the initial intention of the study was focused upon an active feedlot, cattle were removed from the pens in July 2003. Therefore, the year of analysis was conducted on an inactive feedlot.

Evaluation of a water balance involved determination and measurement of processes that add water (input) or remove water (output) from the system along with changes in water storage of components within the system (Figure 1.1).

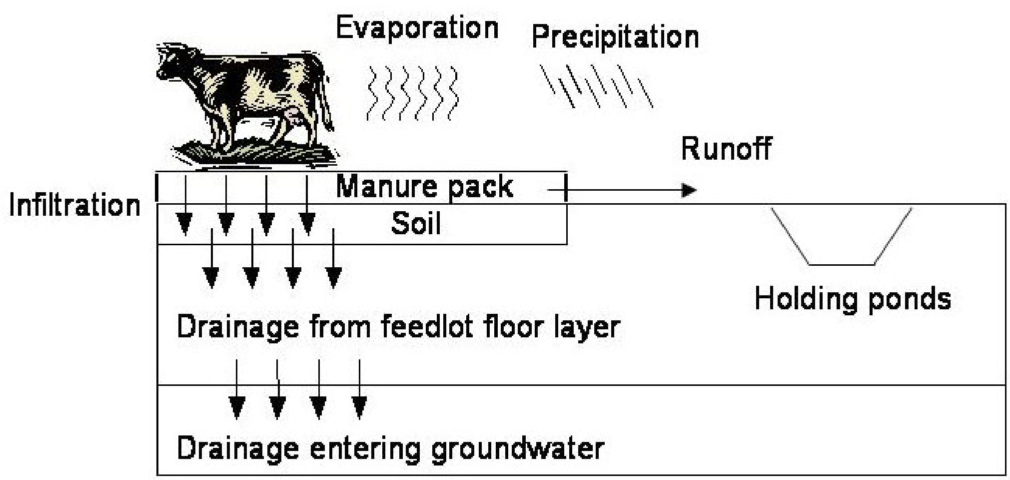

Figure 1.1. Conceptual feedlot diagram showing water inputs and outputs.

The following water balance components and processes were determined or measured for a one year period for the pen floor area of a feedlot:

a. precipitation input;
b. water input in the form of animal manure and urine;
c. potential and actual evaporation;
d. runoff;
e. infiltration into manure pack and underlying soil;
f. change in manure pack moisture;
g. change in soil moisture to a depth of 0.6 m; and
h. water draining below a depth of 0.6 m

In order to meet this objective, the water balance of an inactive feedlot pen in Saskatchewan was calculated for one year using available meteorological data to quantify precipitation and evaporation parameters. Soil and manure sampling provided information regarding the change in soil and manure moisture contents. Infiltration (which will help to quantify the change in moisture content and runoff parameters) was measured in the field with a double ring infiltrometer and a rainfall simulator, and assessed with laboratory measurements of saturated hydraulic conductivity. Runoff was measured on-site from actual rain events using a weir, as well as modeled from infiltration-runoff measurements made with the rainfall simulator. Measurement of soil moisture changes with depth was used to assess drainage, while the current literature was used to estimate drainage below a depth of 0.6 m. Lastly, actual evaporation was calculated by difference method from the other measured parameters in the water balance equation.

2. LITERATURE REVIEW

2.1 Water Balance

The soil water balance is a useful tool for hydrological studies. A water balance, when applied to a soil system, describes the fates of precipitation and the various components of water within the soil profile, and is a simple way to quantify soil-water storage, evaporation, and water surplus (Calder 1992).

In addition, the movement and storage of water in surface soils is important for economic and environmental reasons. Rainfall water entering the soil usually replenishes the soil storage reservoir and, subsequently, if the volume of infiltrating water exceeds the storage capacity of the soil root zone, it moves downward through the soil, contributing to recharge of the aquifer below. The water that moves through the root zone has the potential to carry contaminants downward to the groundwater system. If the rainfall rate exceeds the infiltration rate of the surface soil, the excess water can become runoff that moves across land into surface water bodies, carrying contaminants with it.

There have been many studies performed using a water balance to determine the evaporation and seepage losses from earthen manure storages, including studies by Parker et al. (1999b), Ham (1999) and Ham and DeSutter (2000). To date, there has been no research on the use of water balance models to determine the evaporation and seepage losses from feedlot pens. Environmental conditions are different between earthen manure storages and pens and cannot be easily interchanged for research purposes. For example, feedlot pens usually exist under unsaturated conditions, while earthen manure storages are saturated for most of the year. As a result, water balance models for crop field water balances were also a focus for the literature review, as they are unsaturated and allow for drainage, runoff, and evapotranspiration.

Freeze and Cherry (1979) described the components of the water balance in general watersheds as the following:

$$P - AE - D - \Delta S - R = 0 \tag{2.1}$$

where:

P = water added from precipitation (mm),

AE = actual evaporation (mm),

D = drainage (mm)

ΔS = change in soil moisture storage (mm), and

R = runoff (mm)

Lane et al. (1983) also used a water balance to understand the soil-water-plant relationships in the Northern Mojave Desert. The water balance was described as the following:

$$\Delta S = P - R - AE - D \tag{2.2}$$

where:

ΔS = change in soil water (mm),

P = precipitation (mm),

AE = combined evaporation and plant transpiration (mm),

D = seepage below the root zone (mm), and

R = runoff (mm)

As an example, Lane et al. (1983) used the CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) model (Knisel 1980, as referenced by Lane et al. 1983) to estimate evapotranspiration, which was multiplied by a water use efficiency factor to estimate net production of perennial vegetation. The CREAMS model also included a hydrological component made up of two models, the USDA rainfall-runoff model (USDA 1973) and the Green-Ampt infiltration equation (Green and Ampt 1911, as referenced by Lane et al. 1983). Thus, the model predicted runoff and infiltration and performed a water balance by simulating evaporation, plant transpiration, and drainage below the root zone.

Gee and Hillel (1988) performed a review and critique of groundwater recharge estimation methods in arid regions. They reviewed a soil water balance (Equation 2.1) where all of the components used to quantify drainage were measured or estimated, including measured change in soil moisture storage below the root zone with deep drainage lysimeters, as well as calculated as a Darcian flux.

Kizil and Lindley (2002) used an abbreviated soil water budget equation to develop a regression equation to predict runoff using rainfall data at a bison feedlot in North Dakota. They described the water balance as the following equation:

$$\Delta S = P - R \tag{2.3}$$

where:

ΔS = change in soil moisture storage (mm)

R = runoff (mm)

P = precipitation (mm)

Kizil and Lindley (2002) also noted that on a feedlot surface, a non-permeable layer is formed due to compaction, thus ΔS was assumed to be zero through the soil layer.

It is necessary to note that there are several approaches to determining a soil water balance, each of which is presented below. Advantages and disadvantages of each approach and the environments in which they might work the best in were also discussed.

2.1.1 Measured Actual Evaporation and Drainage

Several soil water balance studies have measured both actual evaporation and drainage (Gee and Hillel 1988; Van der Velde 2005). This method has been found to be quite accurate, but requires a great deal of field work and typically incurs great expense for instrumentation.

Campbell and Harris (1977) and Evans et al. (1981), as referenced in Gee and Hillel (1988), measured the change in soil moisture storage with neutron probes coupled with tensiometer measurements. They remarked that these methods provide a reliable measurement of drainage, as the change in soil moisture storage below the root zone can then be attributed to drainage or evaporation. They indicated that errors in water storage values using neutron probes can be kept to less than 10% or less and Rosenberg et al. 1983, as referenced in Gee and Hillel (1988), added that micrometeorological measurements (such as the Bowen ratio and covariance methods) have also been used to measure actual evaporation to within 10% of actual values.

Van der Velde et al. (2005) most recently evaluated different components of the water balance of an agricultural field on an island in the Pacific Ocean. Novel techniques were used to measure transpiration and drainage out of the root zone in a field planted with squash during the 2004 growing season. A heat pulse method was used to measure sap flow in the squash and water flux meters were used to measure and sample drainage for further analysis at a depth of 1 m. Soil evaporation was measured with micro-lysimeters. To evaluate off-season drainage, experiments were carried out to include a part of the off-season wherein deep rooting Guinea grass was quickly established after harvest.

2.1.2 Measured Drainage with Determination of Actual Evaporation by Difference

Other soil water balance studies have measured drainage and then calculated actual evaporation by a difference method from other water balance parameters. Actual evaporation can be calculated using Equation 2.1 from a soil water balance. Since drainage values on the prairies are generally quite low (Allison et al. 1994), actual evaporation can be calculated from the difference of the other parameters.

The instantaneous profile method was applied in successively cropped and fallow (covered) lucerne plots by Krentos et al. (1975) in order to assess the drainage component in a field water balance study. Moisture changes in a layered medium textured soil were monitored with a neutron moisture gauge with concurrent measurements of matric suction by mercury tensiometers placed at 0.3 m intervals up to a depth of 2.4 m. From this data, it was possible to determine the unsaturated hydraulic conductivity of the fallow (covered) plot from which the drainage component over a whole year was determined. Thus, the actual evapotranspiration of lucerne was calculated from soil moisture changes adjusted for drainage.

2.1.3 Measured Actual Evaporation with Determination of Drainage by Difference

Several water balance studies also measured or estimated actual evapotranspiration and then determined drainage by difference (Rushton 1979; Gee and Hillel 1988; Flint et al. 2001). In doing this, Rushton (1979) confirmed that obtaining precise estimates of actual evapotranspiration from various methods such as open water evaporation pans, meteorological data using Penman's equation (Penman 1948), or irrigated lysimeters, pose the greatest problem in this method.

Gee and Hillel (1988) stated that the problem with water balance methods (including simplified water balance models and simulation models of water balance) where drainage is calculated by difference, as opposed to measured directly**,** is the fact that reliability of the recharge calculation (by difference method) depends on the accuracy of the measured components. In many simulation water balance models, potential evapotranspiration was calculated from monthly, daily, or hourly climate data, and from it, an estimate is made of the actual evaporation (AE). Precipitation measurements are hardly ever more precise than ±5% and actual evapotranspiration measurements are rarely more accurate than ±10%, introducing a measure of uncertainty into the calculated recharge. The error for drainage can be especially large for dry environments where recharge may only be 5 to 20 mm per year and actual evapotranspiration can be up to 500 mm.

Allison et al. (1994) commented that the soil water balance technique has been used extensively in temperate areas, but also noted that actual evaporation needed to be estimated accurately and significant runoff must not occur. They also explained that the largest errors in evaporation estimates occur in semi-arid regions because of long periods of time when actual evaporation is far less than that of the potential evapotranspiration, and often equal to that of precipitation.

Flint et al. (2001) also concluded that numerical modeling methods of unsaturated zone flow (where evapotranspiration is measured and drainage is calculated as difference) are unlikely to be successful in arid climates because of the difficulty in accurately measuring hydrological parameters when groundwater drainage rates are low.

2.2 Feedlot Pen Soil and Manure Characteristics

Various physical properties of the soil and manure pack in feedlot pens such as manure pack thickness, bulk density, and antecedent moisture content help quantify water balance parameters such as change in soil and manure pack moisture storage, as well as runoff. Mielke and Mazurak (1976) measured the manure pack thickness at the feedlot they studied to be between 150 and 300 mm. They reported an average bulk density of 1420 kg/m^3 for the soil at the manure/soil interface including the bottom of the manure pack above and the soil below. The bulk density of the soil underlying the manure/soil interface ranged from 1450 to 1850 kg/m^3.

Chen and Hruska (1982) presented the engineering properties of beef cattle manure, including manure density. They found the average particle density of cattle manure ranged from 1000 to 1050 kg/m^3, with higher densities as the total solids content increased to a maximum of 16% total solids by mass. At greater than 16% total solids, the manure started to trap air and the bulk density began to decrease.

McCullough et al. (2001) measured bulk density of a new sandy loam feedlot surface in Texas. Initially, the bulk density of the feedlot floor ranged from 1810 to 1870 kg/m^3. After nine months in operation, the bulk density of the top 150 mm of the soil profile measured between 1730 and 1840 kg/m^3.

Miller et al. (2003) found that the manure pack depth in a feedlot pen in Alberta over a two year period varied from 53 to 95 mm for the pen floor and 139 to 176 mm for the bedding pack (where straw or other material is added to the pen floor to provide a place for the cattle to lie down). They also sampled the top 300 mm of the loam soil and found the bulk densities of the pen floors to be between 1700 to 1870 kg/m^3 and remarked that the bulk densities were highest where cattle traffic was greatest. Finally, they also noted that the moisture content of the surface soil underlying the wet manure pack ranged from 16.2 to 21.9% for the bedding pack and pen floor, respectively.

Kennedy et al. (1999) found that the organic matter content of the soil just below the manure/soil interface was 1.5%. In addition, the chloride content of the manure pack was determined to be 5,600 ppm, and between 410 and 1,729 ppm in soil beneath the manure pack, with an average of 668 ppm.

No studies upon dry manure pack properties could be found, and therefore, there is no way to define the physical characteristics of the dry manure pack. Hydrological properties (infiltration and runoff, etc.) of the manure pack are discussed in Section 2.3.2.

2.3 Infiltration and Runoff

2.3.1 Introduction

Hillel (1998) defined infiltration as the entry and downward movement of water into the soil. This water is supplied from a variety of sources, such as rainfall, snowmelt, and/or irrigation. During a rainfall event, the rate of infiltration, relative to the rate of water supply, determines how much water enters the root zone and how much, if any, will run off. When the water supply to the soil exceeds the rate of infiltration, the excess accumulates on the soil surface or runs downslope. Thus, the difference between the rate of water supply and the infiltration rate is equal to the rate of runoff.

It is also important to discuss the difference between infiltration and saturated hydraulic conductivity. The infiltration rate is the rate at which water enters the soil surface, while the hydraulic conductivity is the ability of the soil to transmit water (Hillel 1998). The initial readings from infiltrometer tests provide the infiltration rate, while the steady-state readings (after a long period of time) provide an estimate of the field saturated hydraulic conductivity (K_s).

As rainfall moves into the soil surface, the rate at which it infiltrates decreases with time. This is known as the infiltration capacity of the soil (Freeze and Cherry 1979). The infiltration rate is quite high initially, but decreases with time to a constant rate, which is known as the steady-state hydraulic conductivity (Hillel 1998). Measurement of the saturated hydraulic conductivity is essential in infiltration-related applications such as runoff estimation and drainage because it is a measure of the movement of a volume of water over an area with time. In addition, infiltration curves can be used to help determine the saturated hydraulic conductivity of a soil. Therefore, field and laboratory methods for measuring saturated hydraulic conductivity were investigated and discussed.

2.3.2 Infiltration and Runoff Characteristics of Feedlots

Feedlots have different infiltration and runoff characteristics than soil. Unlike soils, feedlots develop of a manure/soil interface that must be taken into account in order to perform a water balance. Mielke et al. (1974) found that a manure/soil interface developed from the compaction of cattle hooves and the plugging of soil pores by manure particles, regardless of the texture of the underlying soil. Mielke and Mazurak (1976) found that this manure/soil interface was the most restrictive layer to water and air movement into the top 100 mm of soil.

Sweeten (1996), as referenced in McCullough et al. (2001) stated that rainfall in the Texas High Plains averaged about 460 mm per year, and that 22% of that amount ran off from the manure pack on the feedlot floor. The remaining 360 mm infiltrated into the manure pack and evaporated or moved into the underlying soil.

Kennedy et al. (1999) found that a manure/soil interface developed from cattle hoof action on the feedlot floor where the wet manure pack met the soil surface. In addition, they found that this sealed layer restricted water movement so that there was little to no infiltration into the underlying soil. They also found a high sodium adsorption ratio (SAR) in the manure/soil interface layer, which tends to disperse soil in the layer and reduce the infiltration capacity.

Kennedy et al. (1999) concluded that the antecedent moisture content of the wet manure pack determines when, and if, runoff occurs from the feedlot floor. They commented that the manure pack on the feedlot floor provided a large surface reservoir for precipitation from most storms in Alberta, thus concluding that it takes more rainfall to saturate a feedlot pen surface than a conventional soil surface. In addition, once the manure pack was saturated (measured as approximately 25 mm of rainfall), it then transferred all of the subsequent rainfall to runoff.

McCullough et al. (2001) conducted hydraulic conductivity tests on undisturbed cores in the laboratory and found that the saturated hydraulic conductivity of a feedlot surface decreased by one to two orders of magnitude after a nine-month stocking period, after which time the feedlot surface was sealed with a manure layer.

2.3.3 Infiltration and Saturated Hydraulic Conductivity Measurement Methods

There are many different methods available for measuring and determining infiltration, both in the field, as well as in the laboratory. An appropriate method should be chosen based on the nature of the soil, availability of equipment and expertise, soil water content range for which measurements are needed (saturated or unsaturated), and the purpose for which the measured values are to be used. Since the water balance parameters of the feedlot manure pack and soil for a feedlot in Saskatchewan needed to be determined, the most appropriate field and laboratory methods for determining saturated hydraulic conductivity were investigated and are discussed below.

2.3.3.1 Ring Infiltrometer Methods

Ring infiltrometers can be used to determine infiltration curves, as well as steady-state infiltration (K_s) of saturated soils (Rawls et al. 1992). The ring infiltrometer method as described by Rawls et al. (1992) and Charbeneau and Daniel (1992) consists of ponding water within a cylindrical ring placed just into the soil surface and measuring the volumetric rate of water addition needed to maintain a constant head. This method measures the steady-state field-saturated hydraulic conductivity near the ground surface and variations of the method include the single-ring and double-ring infiltrometers. A double ring infiltrometer allows water to infiltrate soil vertically, thereby eliminating the effect of lateral flow, which biases measurements taken with a single ring infiltrometer.

Because ring infiltrometers pond water on the soil surface, a large portion of this water might infiltrate through cracks or wormholes, and thus result in very large saturated hydraulic conductivity values, which are not representative of the soil matrix. As a result, ring infiltrometer measurements will be more representative of the surface soil and the infiltration characteristics that occur during heavy rainstorm events (Reynolds 1991). In addition, Sakai et al. (1992) determined that double ring infiltrometer field tests followed the Horton equation for cumulative infiltration. In other words, a maximum infiltration rate occurs at the beginning of a rainfall event (or ring infiltrometer test), but reduces to a low and constant rate as the infiltration process continues and the soil becomes saturated (Hillel 1998).

Kennedy et al. (1999) studied the infiltration characteristics of a feedlot with a clay loam soil and discovered that after a sufficiently long time (137 h), the infiltration of a feedlot floor with intact wet manure pack surface (with the infiltrometers driven through the manure pack and into the underlying soil surface) was effectively zero, as limited by their measurement method. With three single ring infiltrometer tests, an initial infiltration rate of between 9.3×10^{-5} and 4.5×10^{-4} cm/s, and an intermediate rate from 3.0×10^{-5} to 4.4×10^{-7} cm/s was observed before a final measurable rate approaching 0 cm/s, relative to the accuracy of the equipment. Kennedy et al. (1999) also found a saturated hydraulic conductivity rate of 7.8×10^{-8} to 1.8×10^{-7} cm/s for the scraped surface of a feedlot pen after 192 h (and after 336 h, the infiltration rate went to zero).

2.3.3.2 Tension Infiltrometer Methods

Tension infiltrometers are designed to accommodate three-dimensional aspects of wetting from a point source in unsaturated soils. Water is allowed to infiltrate into the soil at a rate which is slower than when water is ponded on the soil surface. This is accomplished by maintaining a small negative pressure on the water as it is infiltrating into the soil so that water will not enter the cracks in the soil, but infiltrate into the soil matrix (Reynolds 1991). As a result, the measurements obtained with a tension infiltrometer will be representative of the soil matrix.

Miller et al. (2003) measured the infiltration characteristics at six locations at a feedlot in Alberta using a double ring infiltrometer and a tension infiltrometer. With the double ring infiltrometer, they found steady-state infiltration rates varying from an average of 5.1 x 10^{-7} cm/s for an active pen with the black layer (manure/soil interface) intact and the manure removed two weeks before tests were conducted to 6.1 x 10^{-7} cm/s for an active pen with the black layer removed. For the same feedlot pens using a tension infiltrometer (with a slight positive tension), they discovered higher infiltration rates than that of the double ring infiltrometer, varying from an average of 5.4 x 10^{-5} cm/s for an active pen with no manure pack and an intact black layer (manure/soil interface) to 5.7 x 10^{-4} cm/s for an active pen with the black layer removed.

Miller et al. (2003) remarked that the differences in values between the two methods might be due to spatial variation within the feedlot pens. They also mention the fact that the tension infiltrometer reached steady-state after 30 to 60 min, as opposed to the double ring infiltrometer, which can take up to 2 to 3 weeks to attain steady-state. In addition, the double ring infiltrometer assumes one-dimensional downward flow, but there could have been lateral flow due to capillary forces, soil heterogeneity, and variation of the water depth in the ring. It is important to note that Miller et al. (2003) assumed that ponded infiltration rates (from the double ring infiltrometer) and field saturated conductivity rates (from tension infiltrometer) represented saturated hydraulic conductivity values.

2.3.3.3 Guelph Permeameter and Infiltrometer Methods

The Guelph permeameter is a constant head permeameter that measures field saturated hydraulic conductivity (Rawls et al. 1992). The steady-state rate of water recharge into the unsaturated soil from a 500 mm diameter cylindrical hole (0.15 to 0.75 m depth) is measured (Elrick and Reynolds 1992). Calculations are then made to determine the hydraulic conductivity. Depending on the soil type, tests can take between 30 min and 2 h.

The Guelph infiltrometer method determines hydraulic properties in the surface soil and measures the field saturated hydraulic conductivity (Gupta et al.

1993). It is a disk-type device that can be attached to the main body of the Guelph permeameter. Thus, the Guelph infiltrometer is a special case of the Guelph permeameter, where a slight head of only 2 or 3 mm of water is maintained on the soil surface.

Gupta et al. (1993) studied several methods of determining field saturated hydraulic conductivity, including the double ring infiltrometer, Guelph rainfall simulator, Guelph infiltrometer, and Guelph permeameter. They concluded that the values of hydraulic conductivity can vary significantly among the methods, mainly due to differences in depth of the experimental installations and the relatively large surface area sampled by the rainfall simulator. They also stated that the hydraulic conductivity values determined by the double ring and simulator methods in the field have less variability than those determined by the Guelph permeameter and infiltrometer (due to differences in cross-sectional area of soil sampled under the various techniques) and require fewer measurements to achieve a mean value with a comparable standard of error. They finally noted that the saturated hydraulic conductivity values found by the ring infiltrometer (mean of 1.4×10^{-3} cm/s) and Guelph permeameter (1.4×10^{-3} cm/s) were lower than that of the rainfall simulator (2.9×10^{-3} cm/s) and Guelph infiltrometer (3.4×10^{-3} cm/s).

2.3.3.4 Laboratory Methods (Falling and Constant Head Permeameters)

Laboratory methods for determining saturated hydraulic conductivity were discussed by Charbeneau and Daniel (1992). Saturated hydraulic conductivity is measured by constant-head or falling-head permeameters on undisturbed soil cores, which applies Darcy's law through a saturated soil column of a uniform cross-sectional area.

Mielke and Mazurak (1976) tested several cores of manure pack and soil encased in shrink wrap plastic using a constant head permeameter and found that the hydraulic conductivity of the 100 mm of soil beneath the manure/soil interface to be 28 times higher than that of the manure/soil interface. The hydraulic conductivity of the manure/soil interface was calculated to be between 1.1×10^{-6} and 6.4×10^{-6} cm/s.

McCullough et al. (2001) measured the saturated hydraulic conductivity of a new sandy loam feedlot surface in Texas in the laboratory with a constant and falling head permeameter. Soil samples were collected from three areas (apron, water trough, and bottom) in each of four pens. They reported that soil samples taken from the feedlot floor before the introduction of cattle had a saturated hydraulic conductivity ranging from 9.3 x 10^{-6} to 1.8 x $^{-5}$ cm/s, while samples taken after nine months of stocking ranged from 5.3 x 10^{-7} to 1.9 x 10^{-6} cm/s. As a result, they stated that greater infiltration of water and salts could be expected in the time period before a compacted manure layer forms.

There were no other studies found that investigated the laboratory saturated hydraulic conductivity of feedlot pen soils.

2.3.3.5 Rainfall Simulators

Rainfall simulators sprinkle water to controlled areas to study erosion, infiltration, runoff, and water quality characteristics. This is accomplished by using a rainfall simulator specifically designed to reproduce appropriate rainfall characteristics. Rainfall simulators can be best utilized where the effect of rainfall on surface conditions influences the infiltration rate.

2.3.4 Runoff Measurement Methods

Different types of runoff collection systems and monitoring systems have been used to measure runoff from feedlots (Kennedy et al. 1999; Miller et al. 2003), but rainfall events on the prairies are infrequent, as well as variable in intensity. As a result, it is sometimes more efficient to use a rainfall simulator in an arid environment, as opposed to waiting for actual rainfall events, especially if rainfall-runoff characteristics are required for a soil water balance. Therefore, both runoff collection systems and rainfall simulations will be discussed in this section.

2.3.4.1 Simulated Rainfall

As discussed earlier (Section 2.3.3.5), rainfall simulators can be used for many purposes. The main advantages of using rainfall simulators, as discussed by Tossell et al. (1987), include cost effectiveness, versatility, and portability (although less so than ring infiltrometers), and they provide control of precipitation intensity, frequency, and duration in both field and laboratory studies.

Rainfall simulators can be used to gather many different types of information about a field plot. Tossell et al. (1987) stated that rainfall simulation has become a very effective way of assessing soil erosion, particle detachment, overland flow, and chemical runoff. For example, Sharpley (2001) used rainfall simulators to compare sediment losses from plots having grass filter strips to those lacking filter strips. He also evaluated the effect of no-till and conventional tillage on erosion and phosphorus loss with a rainfall simulator, examined how intensive grazing or trampling affects runoff from pastures, and studied the effect of manure type on potential phosphorus loss.

Tossell et al. (1987) reported that the simulator nozzle height should be kept within 1 to 2 m above the study area and that nozzle water pressure should also operate within certain limits (45 to 100 kPa). Agassi (1999) also stated that nozzles that produce minimal variation in rainfall intensity over the study area and drop size distribution similar to that of natural rainfall are preferred. In addition, Nolan et al. (1997) built a GRS II to study soil erosion in Alberta. They noted that an intensity of 60 mm/h typically represented Alberta storms and that running the simulator at this intensity for 20 min roughly mimicked a one in two year storm.

There has been relatively little research involving infiltration and runoff characteristics of a feedlot pen using rainfall simulators. Most studies used rainfall simulators to determine hydrological characteristics of agricultural field crop plots. For example, Skarberg and Goddard (1994) and Nolan et al. (1997) described the process of developing runoff curves using a Guelph Rainfall Simulator (GRS II). During each simulation, all runoff that exited the plot was suctioned into sample bottles. Runoff from each simulation was then used to determine total runoff and cumulative runoff curves with time. Similarly, the infiltration rate was calculated from the difference between runoff rate and total applied rate of water. This offered the opportunity to create curves of infiltration rate with time for each simulation. These curves were then used to calculate amounts of runoff or infiltration at simulation times representing various types of storms.

Miller et al. (2003) conducted a study on feedlot pens with a Guelph rainfall simulator (GRS II). It was found that the time to start of runoff was mainly affected by the depth of manure pack, moisture content, and pen surface roughness. It was also noted that instantaneous runoff measurements were occasionally in excess of the rainfall rate due to water being released from cattle hoof-print depressions. For a rainfall rate of 54 mm/h, the time to start of runoff varied from 10.7 min for a pen floor to 21.6 min for a bedding pack. In addition, for the same rainfall rate, they also found a runoff rate of 48 mm/h for the bedding pack and 50 mm/h for the pen floor.

2.3.4.2 Actual Runoff (Collection Systems)

Using various runoff collection systems, several feedlot studies quantified the amount of runoff produced from individual precipitation events, which averaged from 9 to 25 mm depth, depending on the particular study (Table 2.1). The values for the coefficient of variation from 70% to 106% indicate that there is a large variation in the amount of runoff produced from individual precipitation events.

Table 2.1. Precipitation and runoff events for several Western Canadian feedlot studies.

Author	Rainfall (mm)	Runoff (mm)	Yield (%)	SCS CN
Kennedy et al. (1999)	79.0	24.5	30.4	67.7
CV (%)	70	105	73	19
Miller et al. (2003)	37.8	8.8	19.4	79.8
CV (%)	90	160	90	20

CV: Coefficient of variation, SCS CN: Soil Conservation Service curve number

Several other studies quantified the amount of rainfall that ended up as runoff at various feedlots in the world (Table 2.2). Coote and Hore (1977) found that for an individual precipitation event, 19 to 25% of the water became runoff in Southern Ontario. Gilbertson et al. (1981) and Lott (1995) as referenced by Miller et al. (2003) found that 36 to 86% and 22 to 50% of rainfall from a precipitation event became runoff in the USA and Australia, respectively.

Table 2.2. Proportion of runoff produced from individual precipitation events for unpaved feedlots in Canada, the United States, and Australia.

Author	% Runoff produced by rainfall events	Area
Coote and Hore (1977)	19 to 25	Southern Ontario
Gilbertson et al. (1981) as referenced by Miller et al. (2003)	36 to 86	USA
Lott (1995) as referenced by Miller et al. (2003)	22 to 50	Australia
Parker et al. (1999a)	38	Nebraska
Kennedy et al. (1999)	16 to 40	Alberta
Miller et al. (2003)	19	Alberta

Kennedy et al. (1999) characterized pen runoff quantity from an operating beef feedlot in central Alberta using a culvert V-notch weir and stilling well system. They recorded 13 runoff events in 1994. In addition, Parker et al. (1999a) studied 13 years of precipitation and runoff data for an unpaved 3,500 head feedlot surface in Nebraska with precipitation varying from 440 to 960 mm per year. They discovered that approximately 38% of rainfall from an individual precipitation event became runoff. No antecedent soil moisture conditions were given.

Miller et al. (2003) studied the quantity of runoff from beef cattle feedlots in southern Alberta. Six runoff events occurred in 1998, three in 1999, one in 2000, none in 2001, and one in 2002. Rainfall duration ranged from 5 to 59 h, and rainfall depth ranged from 4 to 140 mm. The average rainfall intensity ranged from 0.4 to 2.5 mm/h, and maximum intensity was between 1.2 to 15.2 mm/h. They found that there was 0.1 to 56% of the rainfall lost from the feedlot as runoff.

Miller et al. (2003) also stated that prior to rainfall events that created runoff at the feedlot, monthly rainfall exceeded the monthly long-term normals by 102 to 382%, indicating quite wet antecedent conditions. For example, the rainfall of 4 mm that produced runoff at the feedlot had a 5-day antecedent rainfall index of 36.2, which indicates very wet conditions.

2.3.5 Models for Estimation of Infiltration and Runoff

As stated earlier, rainfall events are few and variable on the prairies. In addition, rainfall simulations are time-consuming and labour intensive. Finally, the entire process of rain falling on a manure-covered surface, becoming involved with the manure constituents, and infiltrating or running off is a complex process (Miner et al. 1967). As a result, several runoff models have been used by researchers to predict the occurrence and amounts of runoff. The models investigated were designed for estimating runoff from agricultural plots (Green-Ampt model for runoff estimation), as well as specifically for estimating runoff from manured and scraped feedlot surfaces (USDA rainfall-runoff model).

2.3.5.1 Green-Ampt Model

It would appear that there have been no studies involving the use of the Green-Ampt model for the modeling of runoff from feedlot pens. In general, the model proposed by Green and Ampt (1911), as referenced by Mein and Larson (1973) illustrated the infiltration process as a rectangular piston of water being driven through an unsaturated soil. The amount of infiltration is then approximated from the difference between the total potential at the surface and a constant wetting front capillary potential.

Mein and Larson (1973) developed a simple two-stage model for infiltration under a constant intensity rainfall into a homogeneous soil with uniform initial moisture content. The first stage predicted the volume of infiltration to the moment at which surface ponding begins, and the second stage (which was the Green Ampt model modified for the infiltration prior to surface saturation) described the subsequent infiltration behaviour. They finally derived two cumulative infiltration and infiltration rate equations. They noted that these equations compared very well with experimental data and numerical solutions of the Richards equation for several soil types.

Chu (1997) simplified the two cumulative infiltration equations derived by Mein and Larson (1973) to describe the cumulative infiltration (F_s) required before the infiltration rate (f) equals the rainfall rate (i) and runoff commences. These equations are as follows:

$$F_s = \frac{M_d \Psi_e}{\left(1 - \frac{i}{[Ks(36000)]}\right)} \tag{2.4}$$

where:

F_s = cumulative infiltration (mm)

Md = moisture deficit (m^3/m^3), which is the difference between saturated and antecedent volumetric moisture contents

Ψ_e = suction at the wetting front (mm), from Equation 2.5

i = rainfall rate (mm/h)

K_s = saturated hydraulic conductivity of the soil (mm/h)

The input parameters for Equation 2.4 are all available from on-site measurements, with the exception of the suction at the wetting front, which can be calculated based upon the porosity of the soil. The following equation from Saxton et al. (1985) was used to calculate the wetting front suction of the soil at the River Ridge feedlot:

$$\Psi_e = 10000\ [-0.108 + 0.341\ (\theta_s)] \tag{2.5}$$

where:

Ψ_e = air entry suction (mm H_2O)

θ_s = saturated volumetric moisture content (m^3/m^3)

Once F_s has been determined, then the infiltration rate (f) can be calculated as:

$$f = K_s\left(1 - \frac{M_d \Psi}{F_s}\right) \tag{2.6}$$

Salvucci and Enteckhabi (1994) stated that the Green-Ampt model assumes that the moisture front infiltrates into a homogeneous soil at a uniform initial volumetric moisture content and that this flow is governed by Darcy's law. It was also noted that it is useful to compare the measured and modeled infiltration and runoff rates with time as they vary within a storm event, since the Green-Ampt model describes the variability of the infiltration rate with time.

Yu (1994) analyzed rainfall-runoff data from bare plots in Australia with both the Green-Ampt and a spatially variable infiltration model (SVIM). He concluded that infiltration modeling was particularly important for predicting surface runoff during individual storm events and that the Green-Ampt model tends to underestimate the infiltration rate when the rainfall intensity is high. It was also indicated that the accurate estimation of infiltration is critical to determining surface runoff and went on to say that estimated Green-Ampt parameters based just on soil properties are usually inadequate and parameter values are better calibrated from measured runoff data.

2.3.5.2 USDA SCS Rainfall-Runoff Model

The United States Department of Agriculture (USDA) runoff estimation method incorporates the Soil Conservation Service (SCS) Curve Number model (USDA 1973) to obtain an estimate of runoff from a feedlot pen surface. The model does not take hoof print depressions into account. The equation is as follows:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{2.7}$$

where:

Q = total runoff from the precipitation event (mm depth)

P = amount of precipitation received during the event (mm)

S = maximum soil storage before onset of runoff (mm water)

Based on the curve number chosen, a value for soil storage (S) is calculated as the following:

$$S = \frac{(2540)}{(CN)} - 25 \qquad (2.8)$$

where:

CN = Soil Conservation Service Curve Number

Various researchers (Kennedy et al. 1999; Parker et al. 1999a; Kizil and Lindley 2001; Miller et al. 2003) have used the USDA (United States Department of Agriculture) runoff model to compare actual and predicted runoff from feedlots. An SCS (Soil Conservation Society) runoff curve number was determined using rainfall/runoff data and this number was then used to calculate runoff depth. Runoff hydrographs were developed and runoff volumes were calculated for each rainfall event. These modeled values were then compared to actual runoff values from the respective feedlots to check the accuracy of the runoff model. These researchers found varying curve numbers of between 52 and 97 (Table 2.3), depending on antecedent moisture conditions, stocking density, type of feedlot floor, and storage values of the manure pack.

Table 2.3. Summary of USDA curve numbers for various areas for unpaved feedlots.

Author	Curve Number	Feedlot conditions	Area
Kennedy et al. (1999)	55 to 83	Unpaved, 17m^2/head, variable moisture conditions	Alberta
Parker et al. (1999a)	91 to 97	Unpaved, average moisture conditions	Nebraska
Kizil and Lindley (2001)	93	Unpaved, 46 m^2/head, pens 21 x 22 m	North Dakota
Kizil and Lindley (2002)	82 to 91	Unpaved, 46 m^2/head, pens 21 x 22 m	North Dakota
Miller et al. (2003)	52 to 96	Unpaved, 19 m^2/head, pens 14 x 19.5 m, wet conditions, storage values 0.4 to 7.5	Alberta

Kennedy et al. (1999) reported curve values ranging from 55 to 83 (with an average of 68) for a commercial unpaved feedlot with straw and wood-chip bedding and a stocking density of 17 m^2/head in Alberta.

Parker et al. (1999a) estimated runoff for a seepage model using the USDA method. Runoff curve numbers of 91, 94, and 97 were selected for varying antecedent moisture conditions for an unpaved feedlot surface with precipitation varying from 440 to 960 mm per year.

Burk et al. (2000) also found that runoff curve number varied with antecedent soil water. It also stands to reason, then, that storage values used in the USDA SCS model will also influence the volume of runoff from a feedlot. Miller et al. (2003) found storage values varied from 0.4 to 7.5, indicating a wide range in storage of water on the feedlot floor.

Kizil and Lindley (2001) studied feedlot runoff and the manure management model in North Dakota. The model combined hydrological, nutrient, and sediment transport models to develop a complete feedlot runoff model. SCS curve numbers of 91 and 94 for unpaved and paved lots were chosen respectively. Kizil and Lindley (2002) also determined a runoff curve number for a bison feedlot in North Dakota. Reported SCS curve numbers for unpaved feedlots ranged from 82 to 91, and they found a value of 93 for a bison feedlot using fly ash with a stocking density of 46.2 m^2/head, compared to 23 m^2/head for a Saskatchewan commercial cattle feedlot (Saskatchewan Agriculture, Food and Rural Revitalization 2004) in North Dakota.

By installing an ultrasonic sensor based flowmeter (PCM3) in a drainage pipe at the lower slope end of the pen to collect runoff data every five min, Kizil and Lindley (2002) were able to estimate a SCS runoff curve number for the feedlot. A second technique was to develop a simple linear regression equation to estimate runoff using rainfall data. Runoff hydrographs were developed and runoff volumes (depths) were calculated for each rainfall event. A Microsoft Excel spreadsheet then allowed the calculation of a runoff curve number. It was determined that the use of SCS curve number method in feedlot hydrology provided satisfactory results. They also noted that stocking density is one of the most important factors that affect runoff quantity and quality and that further study is needed to demonstrate the relationship between animal density and curve number.

Miller et al. (2003) found curve numbers from 52 to 96, with an average of 80, for a commercial unpaved feedlot with straw and wood-chip bedding and a stocking density of 19 m^2/head in Alberta. They also noted that although the stocking density was similar to that of Kennedy et al. (1999) (17 m^2/head), the small size of the feedlot pens (14 x 19.5 m) and the greater proportion of manure pack that covered the pen floor (as compared to a commercial feedlot) may have caused several runoff events with a lower curve number (average of 69). In addition, for rainfall events that created runoff at the feedlot, monthly rainfall exceeded the monthly long-term normals by 102 to 382%, indicating quite wet antecedent conditions. Miller et al. (2003) also concluded that runoff models do not take the release of water from hoof-print depressions by the cattle into account. Thus, runoff prediction models for feedlots would underestimate runoff if the release of this water was not considered. This is in relation to the surface storage parameter that is calculated by the USDA runoff model based on the curve number chosen.

2.3.5.3 Snowmelt Runoff Equation

Snowmelt on frozen soils can produce large volumes of water as infiltration is very low due to the presence of ice blocking soil pores. Gray et al. (1985) developed an infiltration equation for snowmelt in prairie agricultural soils (Equation 2.9) based on the relative soil moisture content of the upper 0.3 m of prairie agricultural soils and the amount of water in the snowpack (snow water equivalent, SWE). This equation is irrespective of texture and is a function of frozen soil moisture content. Thus, the amount of runoff (R) will be equal to the snow water equivalent (SWE) minus the infiltration (I).

$$I = 5(1-Sr)SWE^{0.584} \tag{2.9}$$

where:

I = amount of infiltration (mm)

Sr = relative soil moisture content of the upper 300 mm of soil (m^3/m^3)

Sr = antecedent soil moisture content/saturated soil moisture content

SWE = the amount of water in the snowpack at the start of melt (mm)

The infiltration equation described above was developed for measuring infiltration into prairie agricultural soils, not manure pack surfaces. Miller et al. (2003) discovered that of all 11 runoff events from a feedlot pen in Alberta, none were generated by snowmelt. Kennedy et al. (1999) noted that during their study, all snow and manure was removed from the pens before snowmelt runoff could occur.

2.4 Drainage

2.4.1 Introduction

Freeze and Cherry (1979) defined drainage, or groundwater recharge, as the volume of water moving vertically from the soil system into the underlying groundwater system during, or in response to, periods of rainfall. Drainage is also defined as the outflow of water from soil (Hillel 1998) and is affected by the hydraulic conductivity of the soil. Drainage is water that flows beneath the root zone of plants, so it is unavailable for plants to draw up and use for growth.

2.4.2 Methods of Determination

The main methods of estimating groundwater recharge in semi-arid regions were examined to find the best overall method to determine deep drainage at the River Ridge feedlot located about 20 km south of Eston, Saskatchewan. Direct physical methods such as lysimetry were examined, as well as indirect methods such as Darcian estimation of water flux and tracers such as chloride. Direct physical methods are, for the most part, easily applied and have been used extensively in the past, but they are not accurate enough for measuring recharge rates in semi-arid environments because recharge rates are usually quite low (Allison et al. 1994). Indirect methods, such as tracers, on the other hand, are more accurate in semi-arid environments and are a reliable indicator of water movement in the soil.

2.4.2.1 Lysimetry

Shuttleworth (1992) described lysimetery as a method to measure the water movement in a volume of soil. The soil is isolated so that drainage is measured as water leaves the soil, or prevented from leaving altogether. In the case of a weighing lysimeter, the water flowing through the soil is prevented from leaving the lysimeter, thus the change in water storage is determined by weight difference. Drainage lysimeters collect water that flows through the soil from a tube, which can then be weighed.

Lysimeters can provide precise, direct measurement of drainage below the root zone in arid environments (Kitching et al. 1980), but practical problems in construction and operation limit lysimeters from being used over a large area (Rushton 1979). Shuttleworth (1992) pointed out that lysimeters are difficult and costly to install. Allison et al. (1994) reported that lysimeters disturb the soil and vegetation, resulting in different properties as compared to the surrounding conditions. In addition, drainage can only occur when the soil is above field capacity.

2.4.2.2 Darcian Water Flux

The Darcian method of water flux estimates hydraulic conductivity for unsaturated soils. It has limited use in arid environments because recharge is low and can be negative at times (discharge). Allison et al. (1994) stated that water flux estimates are often in error of an order of magnitude or more.

Stephens and Knowlton (1986) and Flint et al. (2002) used measurements of unsaturated hydraulic conductivity and hydraulic gradient to solve Darcy's Law in the unsaturated zone to estimate soil water flux. The soil water flux is equal to the groundwater recharge given by the following equation:

$$D = K(\theta)\Delta H_t \tag{2.10}$$

where:

D = soil water flux ($m^{-3}/m^{-2}s^{-1}$)

ΔH_t = the total head gradient (m/m)

$K(\theta)$ = hydraulic conductivity as a function of moisture content (m/s)

2.4.2.3 Change in Soil Moisture Storage and Field Capacity

Values for antecedent and final volumetric moisture content with depth can also be used to determine if drainage occurs in a soil profile. If the antecedent and final volumetric moisture contents of the soil are known, along with the field capacity, the drainage can be calculated based on the change in soil moisture content with each depth increment. If the soil moisture is above that of field capacity, it is assumed that the excess moisture moves downward through the soil profile. If the soil moisture is at or below field capacity, it is assumed that no movement of soil moisture takes place, and thus, no drainage occurs.

Hillel (1980) noted that the limitations of this technique are that it was meant for use in wet environments, as well as the fact that the field capacity of the soil must be known. In addition, phenomena such as macropore flow can result in inaccurate estimates of drainage with this technique. Advantages of these types of measurements are that tensiometers can be used to measure the hydraulic gradient in the soil with depth so that the direction (upward or downward) and quantity of moisture movement can also be determined.

2.4.2.4 Tracers

Tracers are a more recent development in the measurement of groundwater recharge in the semi-arid and arid areas of the world and their main advantage is that they integrate all of the processes that cumulatively affect water flow in the unsaturated zone (Allison et al. 1994). Gee and Hillel (1988) determined that chemical tracers were a fairly direct method of monitoring seepage toward groundwater and can be introduced deliberately or may already be present in the environment. It was also noted that the method is good for arid regions with low recharge rates.

Allison et al. (1994) described the following three techniques used for estimating recharge rates from tracer profiles in the unsaturated zone: the position of the tracer peak, the shape of the tracer profile in the soil, and the total amount of tracer stored in the profile. It was stated that tracer behaviour is usually a more reliable indicator of water movement in a porous medium, especially in arid environments. It was also indicated that the chloride method appears to be the simplest, least expensive, and most universal for recharge estimation. Also, chloride profiles were found to be uniform in semi-arid areas, indicating very low and relatively uniform rates of groundwater recharge.

Joshi and Maule (2000) stated that tracer behaviour represents a better indicator of water movement in soil than solving water flow equations, especially in the unsaturated zone. It was noted that most often, tracers are used to estimate the magnitude of moisture fluxes. It was confirmed that solute profiles within the vadose zone may be described in three different ways: peak migration method, mass balance method, and profile-matching method. More specifically, the peak migration method gives a quantitative estimate of the recharge flux, the mass balance method enables the mean annual recharge to be estimated, and the profile-matching method gives the qualitative features of a tracer profile. The first method assumes piston flow and all three methods rely on steady-state flow and spatially uniform solute input assumptions.

Joshi and Maule (2000) described the percolation velocity of the peak migration method as the distance to a solute peak divided by the approximate time of its addition and noted that the chloride peak migration provides a direct means for estimating soil-water flux. Joshi and Maule (2000) remarked that the peak migration method assumes that the peaks must have displaced at least the amount of soil water present above them in the profile and that the existing water content profile has reached a steady-state. It was finally noted the possibility of chloride bulges resulting from preferential flow through the root zone after episodes of heavy precipitation.

Flint et al. (2002) argued that chloride in soils can be adsorbed, which may result in shorter estimates of travel times than for water. In contrast, Si (2003) also postulated that the main disadvantage of using chloride as a tracer is that, in certain high clay content soils, its movement through the soil matrix is up to three times faster than the actual drainage rate. This is due to anion exclusion effects that cause preferential flow, as well as immobile water in the soil matrix that result in a faster velocity and an inaccurate estimate of drainage rate.

2.4.3 Drainage Characteristics in the Prairie Provinces

Using the chloride peak migration method, Joshi and Maule (2000) found a groundwater recharge rate below 1.5 m for a Saskatchewan cropped field (clay to clay loam soil) of 9 to 11 mm/year. Dyck et al. (2003) studied the long-term (>30 year) movement of a chloride tracer applied to the soil surface of an agricultural field and calculated a deep drainage estimate of 3 mm/yr. They noted that this recharge rate was within the range of other estimates for the Canadian Prairies. It is important to note that these studies were not done on a feedlot. For a feedlot in the prairies, drainage might be different given the presence of a manure pack, a well compacted soil surface, and the lack of plants.

Maule and Fonstad (2002) used a mass balance chloride tracer technique to determine the depth and rate of manure seepage and soil moisture flux beneath several feedlot pens. They measured solute concentrations from soil cores beneath three 30-year old feedlots in Saskatchewan. The study indicated that although most of the manure solutes are moving as slow bulk flow (matrix), there is sufficient bypass flow to contaminate nearby shallow piezometers. Using this technique (and corrected for diffusion), the moisture flux beneath the pens below 1.0 m depth was determined to be between 2 and 6 mm per year. Maule and Fonstad (2002) noted that this was not atypical for the prairies. This study was the only one found measuring drainage under feedlot pens using a tracer technique.

2.5 Moisture Input from Cattle

Cattle consume and excrete water depending on the weight of the cattle and the air temperature. According to Irwin (1992), a 270 kg beef cow consumes 15 to 30 kg of water per day at 20°C. Numbers from Australia reported by Graham et al. (2002) report that water consumption of feedlot cattle varies from 3 to 5 kg per kg of dry matter intake at a temperature range of 15 to 25°C (Feedlot FLL 2002). If the cattle consume 2.7 to 3 kg of dry matter for every 100 kg of body mass, a 270 kg animal will consume approximately 44 kg of water per day.

Calculations from information provided by Davis et al. (2002) shows that between 4.8 and 5.2 L of water are excreted for each 100 kg of feedlot cattle under Colorado conditions. Information provided by Alberta Agriculture, Food and Rural Development (2002) indicated that based on 1000 kg of live animal mass, approximately 58 kg of total manure (including both feces and urine) is produced per day. Total solids in the manure amount to approximately 8.5 kg, which indicates that 49.5 kg is liquid portion. Density of the manure as excreted is 1000 kg/m^3, indicating the volume of liquid produced to be approximately 50 L per day per 1000 kg of feedlot cattle. This converts to an addition of approximately 0.78 L/m^2 per day for a 360 kg animal, based on typical stocking density of 23 m^2/head (Saskatchewan Agriculture, Food and Rural Revitalization 2004).

In addition, as temperature increases, water intake by the cattle increases (Alberta Agriculture, Food, and Rural Development 2002), but it is unknown what effect this has on the volume of water excreted by the cattle.

2.6 Actual Evaporation

2.6.1 Introduction

A determination of actual evaporation is needed in the soil water balance because it is necessary to know what happens to precipitation once it falls on the feedlot floor. Actual evaporation measurements will determine how much, if any, moisture that is absorbed into the manure pack, but does not run off will evaporate back into the atmosphere.

It is important to note that an estimate of potential evaporation was required for the soil water balance at the River Ridge feedlot as a reference for actual evaporation, and therefore, several methods were investigated. Amatya et al. (1995) indicated that most current hydrological (including soil water balance) models require an accurate estimate of potential evapotranspiration and added that many equations for calculating this potential evapotranspiration from weather data have been developed and tested. They noted that it is generally accepted that Penman based daily evapotranspiration equations are the most accurate.

2.6.2 Methods of Determination of Actual Evaporation

Several methods of determining actual evaporation were investigated and discussed previously. Since drainage values on the prairies are generally quite low (Allison et al. 1994), actual evaporation can be calculated accurately from the water balance of the other parameters. Thus, it was decided that the most accurate method for determining actual evaporation at the River Ridge feedlot was that of measured drainage and determining actual evaporation by difference (Section 2.1.2).

Several water balance studies measured actual evaporation and calculated drainage by difference (Rushton 1979; Gee and Hillel 1988; Flint et al. 2001), but methods such as open water evaporation pans, meteorological data using Penman's equation (Penman 1948), or irrigated lysimeter evaporation measurements are rarely more accurate than ±10%, introducing a measure of uncertainty into the calculated recharge (Allison et al. 1994). In addition, the measurement of actual evaporation by the methods mentioned above is unlikely to be successful in arid climates because of the difficulty in accurately measuring hydrological parameters when groundwater drainage rates are low (Allison et al. 1994).

Thus, actual evaporation for a feedlot can be calculated using the following adaptation of the Freeze and Cherry (1979) equation for a soil water balance:

$$AE = P1 + P2 - D - R - \Delta S - \Delta MP \quad (2.11)$$

where:

AE = actual evaporation (mm)

P1 = water added from precipitation (mm)

P2 = plus water added from cattle (mm)

D = drainage (mm)

R = runoff (mm)

ΔS = the change in soil moisture storage (mm)

ΔMP = the change in manure pack moisture storage (mm)

2.6.3 Evaporation Characteristics of Feedlot Pens

No literature was found in relation to evaporation characteristics from feedlot pens (manure pack or scraped soil surface). Retention characteristics, drainage, and moisture holding capacity of the manure pack would be useful to know for the water balance, but no literature was available to describe these parameters.

2.7 Summary

To date, there have been no studies defining the water balance of a feedlot pen, but soil water balances in general and their associated parameters have been studied for many years and are well understood. Available literature for active feedlots has quantified several parameters of the soil water balance, including the estimate of moisture addition from cattle, the amount of runoff that can be expected from rainfall events (through actual measurements, as well as rainfall simulations and modeled runoff), the amount of moisture that will likely infiltrate into the soil beneath the manure pack (mainly through field measurements), and a measure of drainage and actual evaporation. Literature regarding the evaporation properties of the manure pack is lacking, as well as studies involving the determination of laboratory measured saturated hydraulic conductivity of feedlot soils.

3. MATERIALS AND METHODS

3.1. Study Site Location and Description

The study site was the River Ridge feedlot, which is located approximately 20 km south of Eston (Figure 3.1) and about 50 km southeast of Kindersley on the north side of the South Saskatchewan River. It is located in Rural Municipality of Snipe Lake (#259) on the southwest quarter of Section 28, Township 23, Range 20, West of the 3rd meridian.

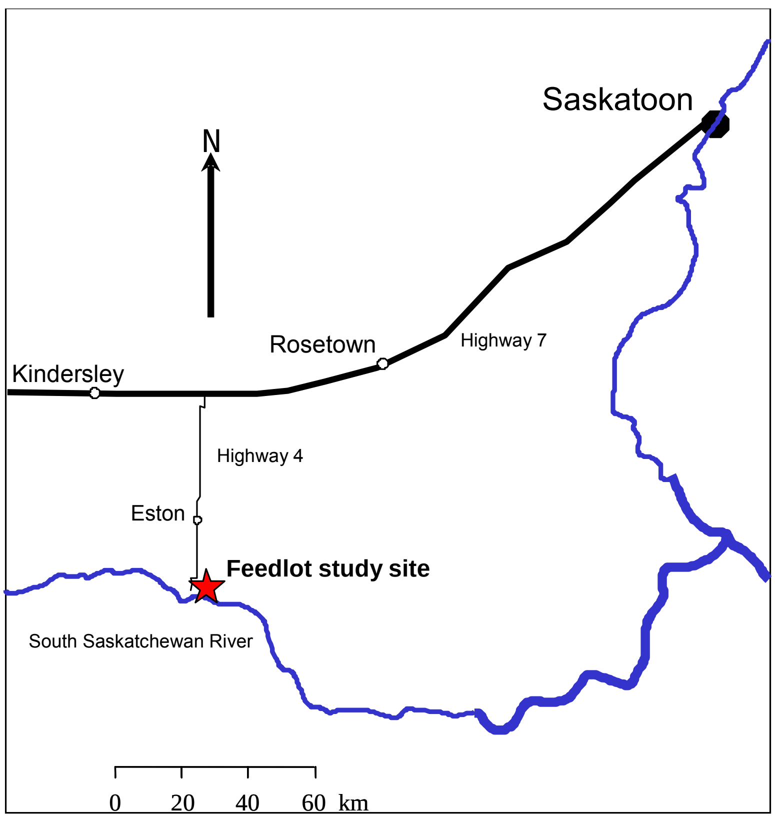

Figure 3.1. Location of feedlot study site (adapted from Map point MSN, 2004).

The feedlot was first established in 1996 as a community co-op venture consisting of eight pens, each 75 by 75 m in area. During 2002, another 8 pens were established immediately to the north of the previous pens and were stocked by the end of summer 2002 (Figure 3.2).

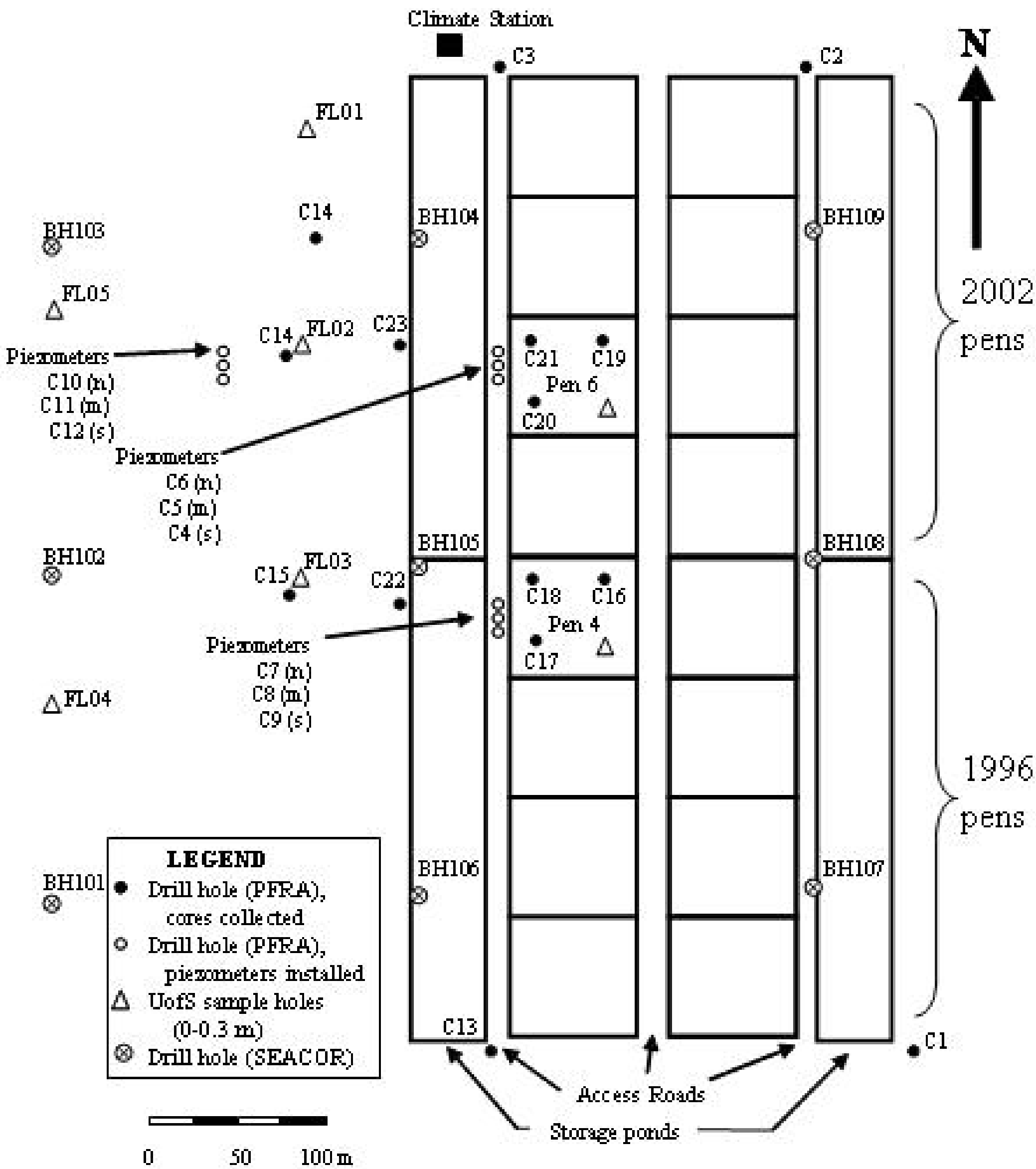

Figure 3.2. River Ridge Feedlot; layout of pens, drillholes, piezometers, and U of S sample holes (Maule, 2002).

While the pens were in operation, the stocking density of each pen was approximately 56 m^2 per head (calculated from 100 backgrounding cattle weighing 360 kg each). The stocking density used at the feedlot was less than that of other typical earthen pen feedlots in the province, which is generally about 23 m^2 per head (Saskatchewan Agriculture, Food and Rural Revitalization 2004) for feeders up to

340 kg. There were cattle present in pen 4 until August 2003 and until July of 2003 in pen 6 when the feedlot was shut down. Bedding consisted of straw, and the pens were cleaned in the fall of each year. In addition, the study feedlot pens were built with a 1.5% downward slope to the west to prevent ponding of water in the pens.

It is important to note that pen 4 and 6 were of different ages. At the time that the feedlot shut down, pen 4 was in operation for 7 years and pen 6 for only one year. This difference in age might affect the physical and hydrological properties of the manure pack and soil, and therefore must be presented and investigated as to the effects on the soil water balance. It is expected that there will be few differences in physical properties (such as manure pack thickness, bulk density, and texture) between the two pens, but that hydrological properties such as saturated hydraulic conductivity and drainage might be quite different, which could affect the overall water balance of the feedlot pen.

Section 28 and much of the sections adjacent consist of glaciolacustrine material with hummocky surficial features (PFRA 1978). SEACOR (1995) drilled a number of 8 to 9 m deep core holes within and immediately adjacent to the feedlot, and found the profiles to consist primarily of sand and silt with interbedded deposits of clay and clay till. Poorly graded, fine sand was the predominant surficial deposit across the site and varied from a minimum thickness of 0.6 m to 7.3 m. The hydraulic conductivity of the sand was estimated to be in the order of 1×10^{-4} to 1×10^{-5} cm/s (SEACOR 1995). The groundwater table was estimated to be between 5 and 8 m in depth, as this was the depth that seepage conditions were encountered by SEACOR (1995) during drilling. The SW ¼ of Section 28 is 648 m in elevation and varied by 1 to 2 m across the site. The South Saskatchewan River is located approximately 5 km south of the feedlot and is at an elevation of 520 m.

Soils of this section, as described by the Snipe Lake Soils Report (Saskatchewan Soil Survey 1994), are a complex of Birsay - Fox Valley soils of fine sandy loam to silt loam in texture. Slopes ranged between 0.5 and 5% and the surface form is expressed as undulating with some dissected erosional features. Birsay soils are brown chernozemic soils formed from loamy lacustrine materials that may be calcareous in nature, whereas Fox Valley are also brown chernozemic soils but formed from silty lacustrine materials. Neither soil type has salinity areas. They are class 4 agricultural capability, having severe limitations that restrict the range of crops (marginal for sustained production) due to poor water holding capacity of the soil. More than half the soils of this complex may be alkaline in pH (>7.5). The soil may be susceptible to moderate wind erosion if there is poor residue protection (Saskatchewan Soil Survey 1994).

Long-term precipitation (1971-2000, Environment Canada 2004) from the nearest Environment Canada meteorological station, Eston (located 20 km to the north of the feedlot site), was 297 mm per year, of which 73.5 mm occurred during winter (November through March) and 224 mm during April through October (Environment Canada 2004). The average monthly temperature for Eston varied from a minimum of -14.3 ºC in January to 18.1 ºC in July (Environment Canada 2004). For the same period Kindersley was slightly cooler, with an average monthly temperature of -14.5 ºC in January and 17.8 ºC in July (Figure 3.3). Kindersley was slightly wetter with an annual precipitation of 326 mm.

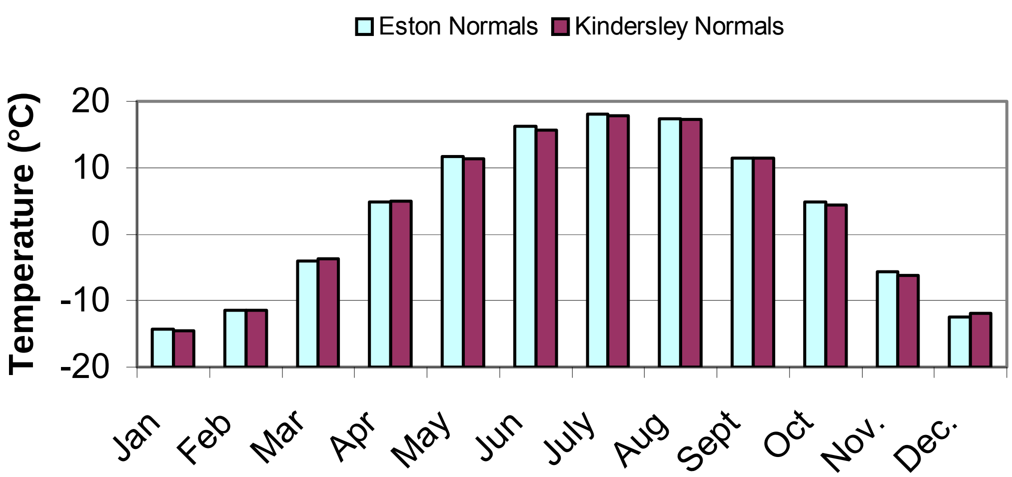

Figure 3.3. Long term temperature normals for Eston and Kindersley (1971-2000).

3.2 Field Instrumentation and Sample Protocol

3.2.1 Precipitation and Meteorological Data Measurement

An automated meteorological station and data logging equipment were installed on August 28th, 2002 with a CR10X data logger (Campbell Scientific, Logan, UT). Meteorological data of wind speed and direction, air temperature, relative humidity, precipitation, and solar radiation were measured for the purposes of determining potential evaporation. The weather station was battery powered and consisted of a data logger and sensors mounted on a tripod. The meteorological station measured sensors every 30 s and recorded the 30 min average in the CR10X data logger.

The meteorological data for the monitoring period from September 2003 until August 2004 was only about 40% complete (162 days out of 365) due to equipment malfunction and changes in trained personnel, as well as the difficulties in maintaining equipment due to the distance between the feedlot site and Saskatoon. The meteorological station at the feedlot was non-functional from September 27th to October 26th, 2003, December 8th, 2003 to May 21st, 2004 and August 8th to 31st, 2004. In order to fill gaps in this incomplete data set, meteorological information was used from the Environment Canada climate station at Kindersley, SK (Environment Canada 2004).

3.2.2 Soil Measurements

3.2.2.1 Time Domain Reflectrometry (TDR) Probe Installation

Soil moisture in the pens and the adjacent agricultural field to a depth of 1.2 m was measured with a time domain reflectrometry (TDR) system (MoisturePoint MP-917 by Environmental Sensors Inc, Victoria, BC). The TDR probes themselves consisted of two 200 mm long, stainless steel rods running parallel to each other attached to a terminal with a single diode. Technical details and construction methods for this type of probe were described by Young (1995).

Installation of the TDR probes in the feedlot pens, as well as the adjacent agricultural field, was described by Tang et al. (2003). A 25 mm diameter hand auger was used to core down to a set depth (eg. 1.0 m) and then the TDR probe with extension was pushed in so that the exposed rod was inserted into the soil between 1.0 and 1.2 m depth. The probes in the adjacent agricultural field were installed in a circle "nest" so that they could be easily accessed. Volumetric moisture measurements were conducted at 200 mm depth increments every four weeks from August 2003 to August 2004. Measurements were not taken during the winter, as the soil was frozen. The probes in the feedlot pens (one set in pen 4 and two in pen 6) were installed from 0.6 to 1.2 m depths (0.6-0.8 m, 0.8-1.0 m, and 1.0-1.2 m) on August 28th, 2003.

Soil volumetric moisture contents, as measured by TDR probes in the pens, were used to determine the change in soil moisture storage over the monitoring period (Sept. 2003 to Aug. 2004), as well as drainage.

3.2.2.2 Disturbed and Undisturbed Soil Sampling

Undisturbed samples of soil from beneath the soil surface were taken in September 2003 in 50 mm depth intervals in a 75 mm diameter steel casing core. The cores were attached to a 25 mm diameter steel rod and driven into the ground with a weight and hammer. Cores from depth intervals of 200-250 mm and 400-450 mm were saved for later measurement of bulk density, volumetric moisture content, and saturated hydraulic conductivity. These particular depths were used as representative depths from 0 to 600 mm. Four to five samples were taken at each depth in each pen in September of 2003, for a total of 18 samples. Due to material hardness and concern about obtaining truly undisturbed samples with the coring device, the samples at 0-50 mm and 50-100 mm depths were taken as large clods (approximately 50 mm wide and 20 mm high). It is important to note that all holes (from which disturbed and undisturbed samples were taken) were backfilled with soil from an adjacent alley and packed down after taking samples.

Disturbed soil samples were taken with a 25 mm diameter hand auger at depths of 0-200 mm, 200-400 mm, and 400-600 mm beneath the soil surface in the feedlot pens. Three samples were taken at each depth interval in each pen from beneath the manure pack, as well as from beneath areas of the pen with the dry manure pack scraped away, for a total of 36 samples on each sampling date. Three small areas of the pen surface were scraped in September of 2003 for the rainfall simulation tests and left bare for the remainder of the monitoring period.

Samples were taken every two weeks from July to August of 2004 and once a month for September and October. The samples were placed in Ziploc bags, labeled, and placed in a cooler with ice for transport to the laboratory. The soil samples were used to determine the change in soil moisture in the top 0.6 m of soil as based on the change in volumetric moisture content for each depth interval.

The bulk density of disturbed soil samples taken with the hand auger were assumed to be the same as that of the undisturbed core samples for the same depths. The gravimetric moisture content of the disturbed soil samples were then determined. The volumetric moisture contents of the soil beneath the manure pack and the soil from areas with no manure pack were used to determine the change in soil moisture with time in the top 0.6 m of the soil over the monitoring period.

3.2.2.3 Soil Sampling Before and After Rainfall Simulations

Disturbed soil samples of 50 mm increments from the surface to 200 mm depth and 100 mm increments from 200 to 600 mm depth were collected in September of 2003 both before and after simulated rainfall trials to determine initial and final moisture contents. For four of the rainfall simulations, samples were only taken in 100 mm increments to 200 mm depth (all in pen 4). Thus, in total, 32 samples were taken in pen 4 (16 to 200 mm depth and 16 to 600 mm depth), and 64 samples in pen 6 (to 600 mm depth). A 25 mm diameter hand auger was used to take the samples. They were placed in Ziploc bags, labeled, and placed in a cooler with ice, for transport to the laboratory. The volumetric moisture content of the disturbed samples both before and after rainfall simulations was determined with the use of bulk density measurements from the undisturbed soil cores.

The disturbed samples described above were also used in particle size analysis. Three samples from each pen from 0-50, 50-100, 100-150, and 150-200 mm depths were used and two samples from each pen from 200-300, 300-400, 400-500, and 500-600 mm depths were used for particle size analysis.

Nineteen of the soil samples taken before the rainfall simulations from beneath the dry manure pack, as well as from the scraped soil surface were also used for the determination of change of soil moisture from 0-600 mm (Table 3.1). The volumetric moisture content of the disturbed samples was then determined.

Table 3.1. Total number of soil samples taken for each depth interval before rainfall simulations.

Depth Interval	MPS # of samples	S # of samples
0-200 mm	3	6
200-400 mm	2	3
400-600 mm	2	3

MPS: Soil beneath the manure pack, S: Soil without manure pack cover.

3.2.3 Manure Sampling

3.2.3.1 Wet and Dry Manure Packs

As the dry and wet manure each have their own unique set of properties, including bulk density and volumetric moisture content, their measurement and discussion are separated in this thesis. The wet manure pack was defined as the normal manure pack that results from the presence of cattle in the pens, (including hoof action and the addition of urine and feces from the cattle themselves) or that resulting from a deep pack that has not completely dried out (Figure 3.4). This wet manure pack remained in certain areas of the pens at the River Ridge feedlot even after cattle were removed in July/August of 2003.

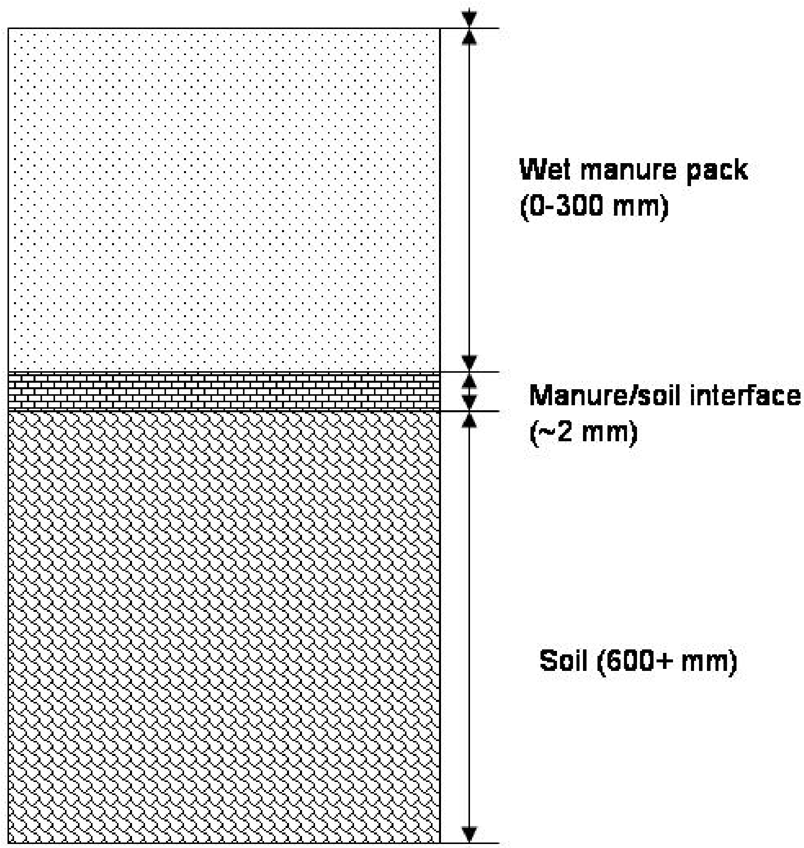

Figure 3.4. Diagram of the physical structure of the wet manure pack profile.

A manure/soil interface was also identified at the feedlot (Figure 3.4). From cores taken from the feedlot, this layer was visible to the naked eye and was distinguishable from the manure pack and soil in that it appeared to be a thin (2 to 3 mm thick) black line in between the two. The depth to the manure/soil interface within the 50 mm undisturbed cores ranged from 10 to 35 mm. Thus, the material above the manure/soil interface consisted of wet manure pack, and the material below it was soil.

The dry manure pack, on the other hand, was characterized by two distinct layers that resulted from the drying out of the wet manure pack. The granular layer of the dry manure pack was a dry, loosely held together granular material (2 mm to 50 mm diameter aggregates), which formed after the cattle were removed from the pens. Beneath the granular layer was a compacted manure layer of the dry manure pack, which was generally much harder, wetter, and denser than the granular layer above (Figure 3.5). Finally, a manure/soil interface was identified between the compacted manure layer and the soil surface, from the visual observation of a black, shiny surface on top of the soil when the compacted manure layer of the manure pack was chipped away.

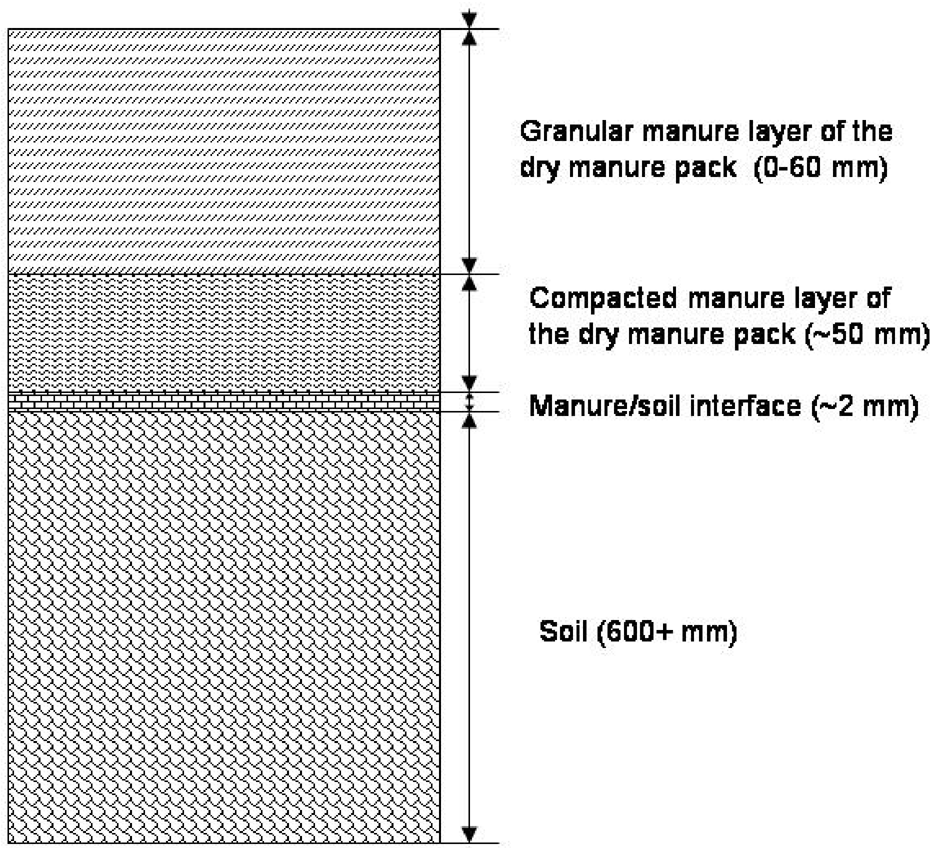

Figure 3.5. Diagram of physical structure of the dry manure pack.

Measurements of the dry manure pack were conducted during the study period (September 2003 to August 2004) and samples were taken from the feedlot pens (Figures 3.6 and 3.7) for laboratory analysis of moisture content and bulk density.

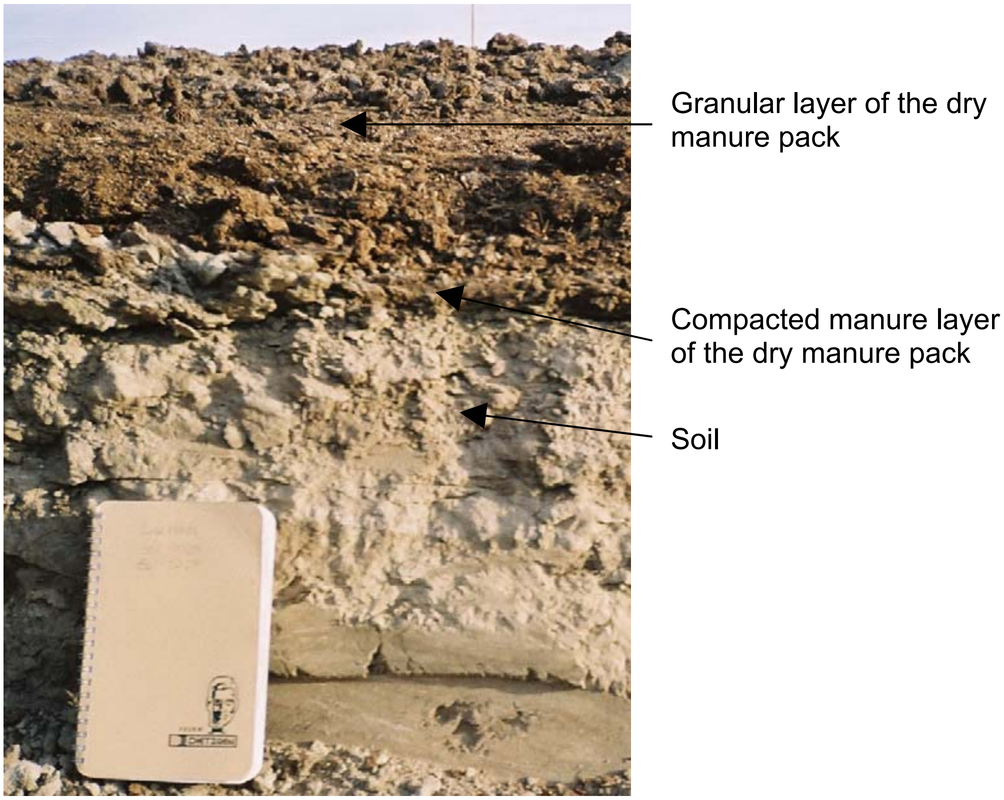

Figure 3.6. Granular layer of the dry manure pack, compacted manure layer of the dry manure pack and soil in feedlot pens.

Figure 3.7. Granular layer of the dry manure pack in feedlot pens.

3.2.3.2 Wet Manure Pack Sampling

Samples of 300 mm length undisturbed wet manure pack were taken from the feedlot in a 75 mm diameter steel casing core in August of 2003. The cores were attached to a 25 mm diameter steel rod and driven into the ground with a weight and hammer. Two cores were taken in each pen. The cores, including the steel casing, were then cut (while still wet) with a band saw into 50 mm increments for laboratory analysis of saturated hydraulic conductivity and volumetric moisture content. It is important to note that the band saw may have caused some disturbance to the manure pack samples within the cores, as it may have sealed cracks or pores at the top and bottom of the cores as it cut. As a result, the surface that had been in contact with the band saw was "roughened" with a box cutter to ensure that any manure pores were not sealed by the cutting.

The disturbed samples of the wet manure pack from the River Ridge feedlot were taken in July to September of 2004, which was 11 to 14 months after the cattle were removed from the pens. Wet manure pack samples were taken with a shovel from 0-200 mm and, if present, 200-400 mm depths. Five samples (three from 0-200 mm depth and two from 200-400 mm depth) were taken in each pen for a total of ten samples at each sampling date. Samples were taken every two weeks from July to August of 2004 and once a month for September and October.

The disturbed wet manure pack samples were used to determine the change in moisture content of the manure pack over the monitoring period. The samples were placed in Ziploc bags, labeled, and placed in a cooler with ice for transport to the laboratory. The wet manure pack samples were used to determine the change in manure pack moisture as based on the volumetric moisture content (using bulk density values from previous measurement) for each depth interval.

3.2.3.3 Granular Layer of the Dry Manure Pack Sampling

Disturbed samples of the granular layer of the dry manure pack were collected with a shovel before each rainfall simulation. The samples were placed in Ziploc bags, labeled, and placed in a cooler with ice for transport to the laboratory. Five samples were taken in September 2003 in each pen, for a total of 10 samples. The samples were taken to determine bulk density, as well as initial and saturated volumetric moisture contents, to calculate the change in moisture content of the dry granular layer.

3.2.3.4 Compacted Manure Layer of the Dry Manure Pack Sampling

Disturbed samples of the compacted manure pack were collected with a 25 mm diameter hand auger both before and after simulated rainfall trials. The samples were placed in Ziploc bags, labeled, and placed in a cooler with ice for transport to the laboratory. Samples were taken in September 2003 before and after each rainfall simulation. The samples were taken to determine initial and final moisture contents to help with the interpretation of infiltration through the compacted manure pack into the underlying soil.

3.2.4 Runoff Sampling and Measurements

Runoff was planned to be determined from a weir runoff collection system, as well as from water depth within the adjacent runoff storage ponds (Figure 3.2). These natural runoff measurements, however, resulted in no measured runoff events due to the combination of rare runoff events (once a year, at most), what appeared to be high infiltration rates of the storage ponds (not measured), and equipment failures.

Saturated hydraulic conductivity measurements were also conducted at the River Ridge feedlot using a rainfall simulator and a double ring infiltrometer, which were then used to help define runoff characteristics from the scraped soil surface and manure pack. Thus, rainfall simulation trials on the scraped soil surface and manure pack, as well as measurement of soil properties (texture, hydraulic conductivity, moisture retention, and moisture content) in combination with theoretical runoff/infiltration models, were used to provide estimates of runoff for the water balance.

3.2.4.1 Guelph Rainfall Simulator II (GRS II)

Infiltration and runoff rates at the River Ridge feedlot were measured with a modified Guelph Rainfall Simulator based on a design by Tossell et al. (1987, 1990) from September 4th to September 18th, 2003 (Figure 3.8 and 3.9).

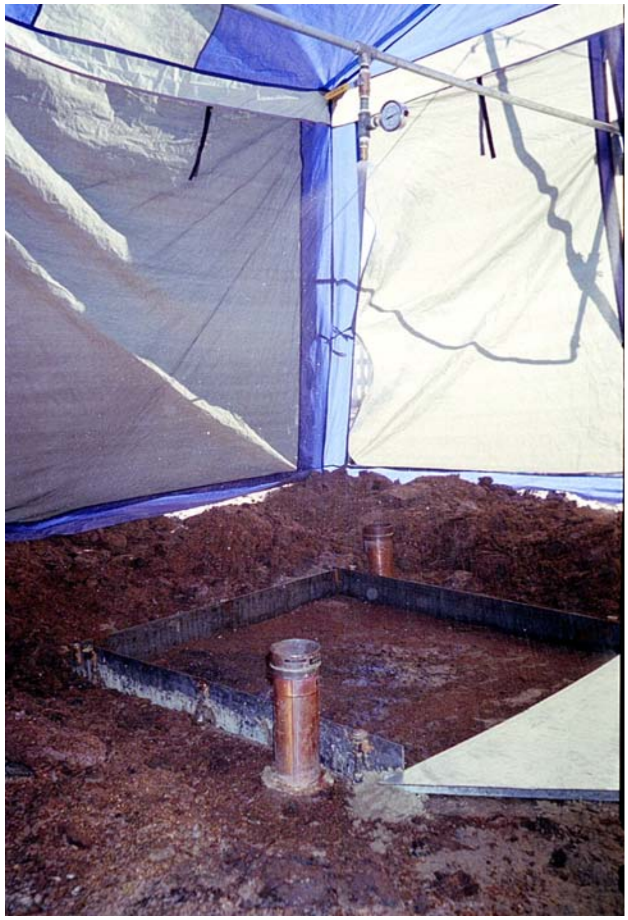

Figure 3.8. Nozzle and collection area set up for rainfall simulations in feedlot pens.

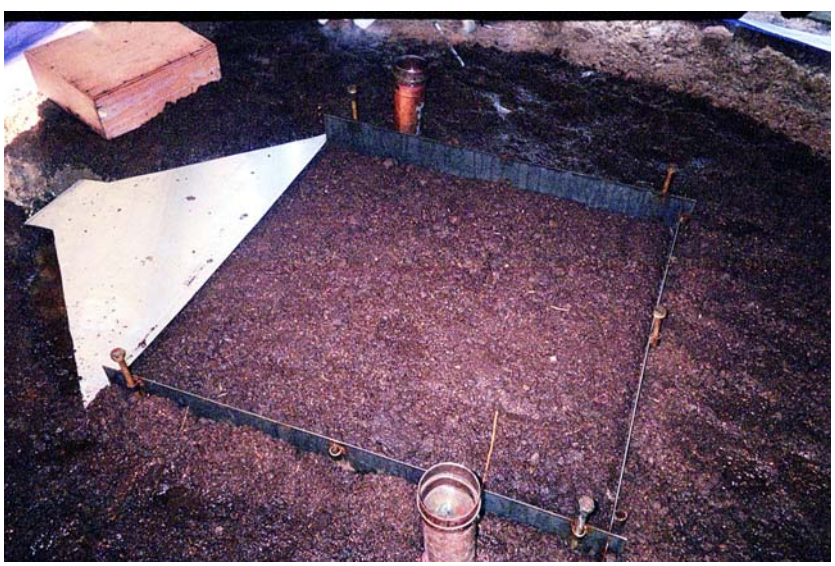

Figure 3.9. Rainfall simulation set up on manure pack in feedlot pen.

The rainfall simulator consisted of a nozzle suspended over a 1.0 m^2 measurement area. A consistent rainfall intensity was simulated with selection of an appropriate nozzle type, the height of the nozzle over the plot, and the water pressure at the nozzle. A 14W 1/4" nozzle was set 1.10 m above the ground surface using water pressures varying from 60 to 100 kPa (to achieve rainfall rates of between 34 and 68 mm/h). A range of rainfall intensities was used because it was unknown as to what intensity of rainfall would produce runoff at the feedlot. As the lower rainfall intensities (34 mm/h) did not generate runoff in a reasonable time frame (several h or more), the intensity was increased.

Three uniformity tests were performed on the rainfall simulator. Operating conditions were the same for that of field measurements where a 14W 1/4" nozzle was set 1.1 m above the ground surface at approximately 100 kPa pressure. Rainfall intensity was measured with nine rainfall collectors which were placed in a grid pattern inside as well as outside the edge of the 1 m^2 plot area. The depth of water in each rainfall collector was measured after 20 min. The average value of uniformity of the measured rainfall intensity using Equations 3.1 and 3.2 (from Tossell et al. 1990) was determined to be 82.9%.

$$\text{Uniformity} = 100 \times (1 - \text{DEV}) \tag{3.1}$$

where:

Uniformity = uniformity coefficient (%)

DEV = deviation of rainfall intensity

and:

$$\text{DEV} = \frac{(\text{RI} - \text{meanRI})}{(\text{mean RI})(\text{\# of collectors})} \tag{3.2}$$

where:

RI = rainfall intensity (mm/h)

MeanRI = mean rainfall intensity for all rainfall collectors

collectors = total number of rainfall collectors

Pen 4 was subjected to five rainfall simulator trials (two with a manure pack and three with manure scraped off so the soil surface was exposed) and pen 6 had four rainfall simulator trials performed on it (one with a manure pack and three with the manure pack scraped off). In addition, one trial was also run in an adjacent crop field.

Runoff was contained to a 1.0 m^2 area by 3 mm thick metal plates that were driven into the ground to about 15 mm depth (Figure 3.8 and 3.9). These boundary plates demarcated an area so that down hill flow could be collected into a triangular runoff pan (Figure 3.9). The runoff pan directed runoff flow into a hole which was dug at the base of the runoff pan to a depth of approximately 0.3 m. A small ditch leading away from the hole was also dug to ensure that runoff did not fill up the hole. The runoff pan was sloped so that sediment flowed off the pan into a 500 mL mason jar.

Two rainfall collectors were placed along the outside edge of the collection area to determine the rainfall intensity. The simulator and the stopwatch were then started, and the time to start of runoff noted. Runoff samples were collected in 500 mL jars until a constant runoff rate was achieved (three consecutive samples with approximately the same fill time were collected). Each mason jar was labeled as to location and time of collection and the time taken to fill up each jar was noted and recorded. After a constant runoff rate was obtained (three measurements), the rainfall simulator was shut off and the amount of water in the rainfall collectors was measured. The steady-state runoff rate was taken from the average of the last three runoff measurements. The infiltration rate was calculated by subtracting the runoff rate from the rainfall rate.

3.2.4.2 Pen Runoff Measurements

A pen runoff collection and monitoring system was established for two pens from July 1st to August 30th of 2004 (Figure 3.10 to 3.14). Actual runoff from each pen being studied was measured with a collection system comprised of several sections of PVC half pipe (0.6 m diameter) that funneled runoff water to a V-notch weir. Each of the two pens had a small earthen berm (100 mm height) installed at each corner of the lower slope end of the pen to direct all runoff toward the weir.

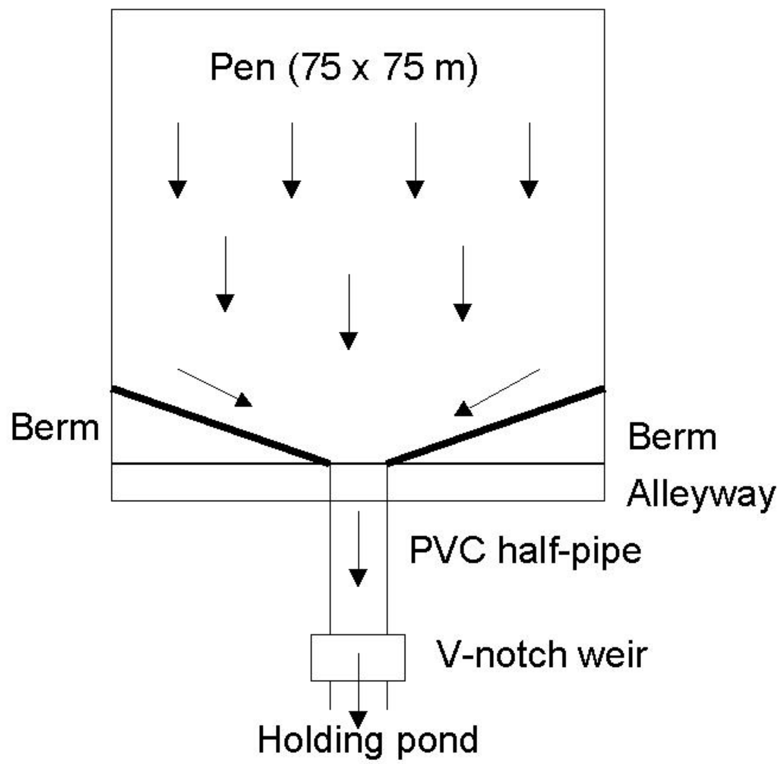

Figure 3.10. Layout of the pen and weir runoff collection system.

Figure 3.11. Construction of the small berm that directed runoff within the pen toward the collection system.

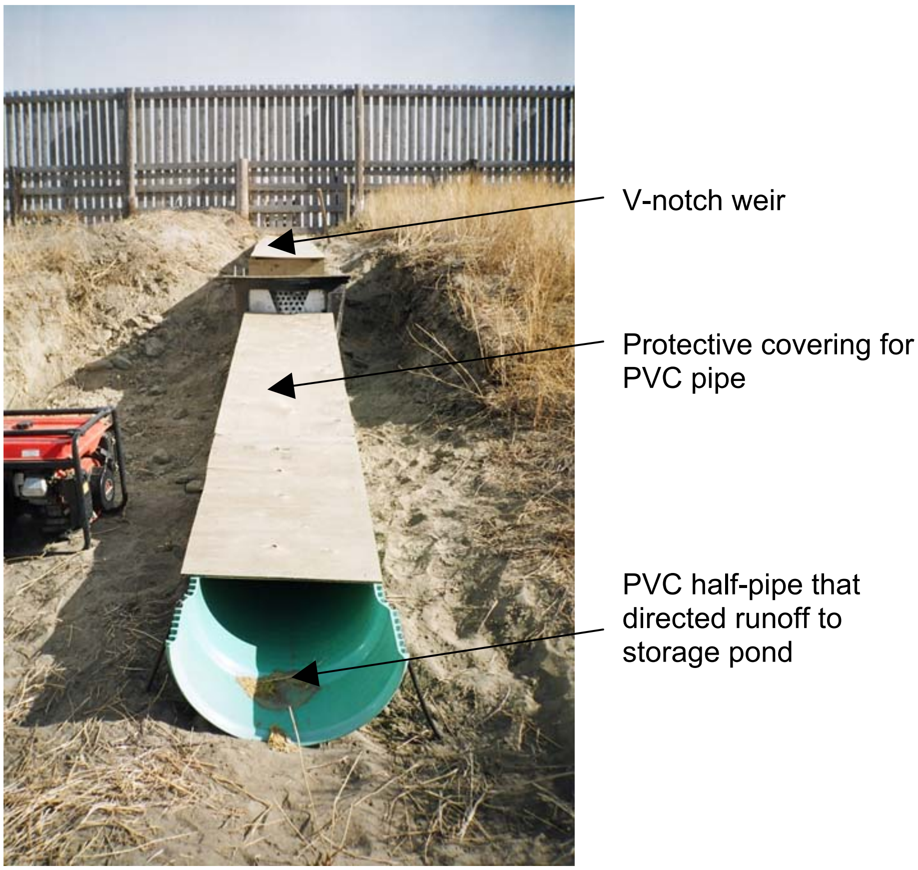

Figure 3.12. PVC half-pipes that channeled water from the pen toward the weir, and then to the runoff storage pond.

Figure 3.13. V-Notch weir, stilling well, and data logger.

Figure 3.14. V-Notch weir, stilling well, and data logger.

Additional soil was filled in around the free flow access pipe that connected the weir to the stilling well. The black tub containing the weir (Figure 3.13 and 3.14) was covered with a piece of treated plywood to keep out debris and additional precipitation. The V-notch weir was 406 mm high, 337 mm wide, and was angled at 22.5°.

The height of water in the stilling well was measured every five min by a pressure transducer placed inside a flexible bladder filled with antifreeze. Since water was allowed to flow freely between the weir and the stilling well, the water level rose and fell equally in both. The stilling well was protected from turbulence so that irregular height recordings were minimized. The pressure transducer in the bladder at the base of the stilling well was calibrated to proportionally measure voltage from the pressure of the water in the well. The voltage read by the transducer was then converted to a height of water.

A TFX11 V2 data logger (Onset Computer Corp., Bourne, MA) programmed in TFX Basic recorded the water level at five minute intervals when the pressure of the water in the stilling well was greater than a minimum voltage of 0.1 volts. The pressure transducer in the stilling well was an Omega PX26-001DV (Omega Engineering Inc., Stamford, CT), which operated within a range of 0 to 1 volts, or 0 to 260 mm water height in the stilling well.

The height of water flowing through the V-notch weir was used to calculate actual runoff flow from the pens based on the following equation from Wigham (1970):

$$Q = C_d (8/15)\sqrt{2g}\tan(\phi/2)H^{5/2} \tag{3.3}$$

where:

Q = flow rate of water through the V-notch weir (m^3/s)

H = the height of the liquid above the bottom of the weir (m)

ϕ = the angle between the side of the notch and the horizontal

C_d = the coefficient of discharge (0.6 for a V-notch weir)

3.2.5 Infiltration Sampling and Measurements

Infiltration of the feedlot floor at the River Ridge feedlot was measured with a double ring infiltrometer (ponded infiltration) in order to help characterize the runoff component of the water balance. The rainfall simulation trials were also used (by difference method between rainfall rate and runoff rate, Section 3.2.4.1) to measure the infiltration rate of the feedlot floor.

3.2.5.1 Ponded Infiltration Measurements

Ponded infiltration was measured with a double ring infiltrometer (Figure 3.15) in September of 2003 as described by Rawls et al. (1992) and Charbeaneau and Daniel (1992). This method gives a measure of the steady-state infiltration (which under various assumptions can be similar to field saturated hydraulic conductivity, Section 2.3.1) of the feedlot floor.

Figure 3.15. Double ring infiltrometer set up.

The rings were hammered into the manure pack to an approximate depth of 30 mm. Due to the hardness of the compacted manure layer of the dry manure pack, as well as the soil underlying the manure pack, the rings were only driven into the manure pack (not through the manure pack and into the underlying soil). The diameter of the inner ring was 310 mm and the outer ring was 610 mm. A constant height of water of 150 mm was maintained in the inner ring throughout the experimental run. Water in the outer ring reservoir was kept at the same height as the inner ring to prevent the lateral movement of water beneath the inner ring, thus maintaining vertical one-dimensional flow. Three sets of measurements were taken in pen 4.

Height drop measurements of water in the inner ring were taken every minute until steady-state infiltration was reached, and every five min after steady-state had been reached. Steady-state infiltration was determined as having three similar drops in height of ponded water over the five minute measurement period. The cumulative infiltration measurements were then converted to an infiltration rate. The following equation given by Hillel (1998) was used for calculating the infiltration rate:

$$q = \frac{-\Delta h}{\Delta t} \tag{3.4}$$

where:

q = infiltration rate or flux ($m^3\ m^{-2}\ s^{-1}$)

Δh = change in height of water in inner ring (m)

Δt = change in time (s)

3.3 Laboratory Methods and Protocol

3.3.1 Particle Size Analysis of Soil Samples

Disturbed soil samples (sampled as described in Section 3.2.2) taken in September of 2003 were subjected to determination of clay and sand fraction using the modified pipette method as described by Sheldrick and Wang (1993).

3.3.2 Organic Carbon and Total Carbon Content of Soil Samples

Organic and total carbon content of six undisturbed soil samples from 0-50 mm depth (sampled as described in Section 3.2.2) was determined using the LECO CR12 carbon analyzer (Leco Corp., St. Joseph, MI) as described by Wang and Anderson (1998).

3.3.3 Bulk Density of Soil Samples

Bulk density tests were conducted on 25 and 50 mm lengths of undisturbed soil samples from 200-250 mm and 400-450 mm depth in a 75 mm steel casing core. The samples were weighed, then dried for at least 24 h at 105ºC and then weighed again. The bulk density of the samples was calculated from the oven dried mass divided by the core volume, as per Culley (1993).

The bulk density of the 0-50 mm and 50-100 mm depth soil samples was calculated according to the clod method for determining bulk density as described by Culley (1993). The samples were weighed, oven dried for 24 h at 105ºC and weighed again. The samples were wrapped tightly in plastic wrap so that moisture was prevented from infiltrating the sample. The samples were then fully submerged in a known volume of water and the displacement determined by measuring the volume before and after. The bulk density was then calculated by taking the oven dried weight of the sample divided by the volume of water the sample displaced.

The bulk density for all the disturbed soil samples taken with the hand auger were assumed to be the same as that for the undisturbed core samples and clod samples for the same depths.

3.3.4 Volumetric Moisture Content of Soil Samples

Disturbed samples (sampled as described in Section 3.2.2) were weighed, oven dried for at least 24 h at 105ºC and then weighed again. The gravimetric moisture content of the soil samples was then determined using a standard water content equation from Topp (1993), described as follows:

$$\theta_g = \frac{M_w}{M_s} \tag{3.5}$$

where:

θ_g = gravimetric moisture content (kg/kg)

M_w = mass of water (kg)

M_s = Mass of solids (kg)

Once the bulk density of the undisturbed samples had been determined, the volumetric moisture content of the samples could be calculated using volumetric soil moisture equation given by Culley (1993). This equation for the volumetric moisture content was described as follows:

$$\theta_v = \frac{\theta_g(\rho_b)}{\rho_{H2O}} \tag{3.6}$$

where:

θ_v = volumetric moisture content (m^3/m^3)

θ_g = gravimetric moisture content (kg/kg)

ρ_b = bulk density of the soil (kg/m^3)

ρ_{H2O} = density of water (kg/m^3)

The initial volumetric moisture content of the undisturbed soil samples was calculated for each depth interval using Equation 3.5 and 3.6 given by Culley (1993). The saturated volumetric moisture content was determined by placing the undisturbed soil samples in a water bath for 24 h to saturate. The samples were then weighed again and the saturated volumetric moisture content was determined using Equation 3.5 and 3.6.

3.3.5 Moisture Retention Characteristics of Soil Samples

Four different depths of disturbed soil samples were tested: 0-50 mm, 50-100 mm, 200-250 mm, and 400-450 mm. The pressure plate testing procedure and equations to determine the moisture retention characteristics of the samples followed that described by Topp et al. (1993). Soil samples were ground and placed in small rings on a 1 bar (100 kPa) ceramic plate. The samples were then saturated on the plate for 24 h prior to being placed in the pressure plate extractor. Once in the extractor, the samples were subject to a 33 kPa suction (to determine field capacity of the samples) until equilibrium had been reached. The equilibrium moisture content of the samples was determined by subjecting the samples to varying lengths of time in the pressure plate extractor (2, 3, and 7 days). Once the moisture content remained the same for two subsequent time periods, equilibrium was assumed to have been reached.

The gravimetric moisture content of the soil samples at each matric potential was then determined using Equation 3.3 from Topp (1993), and then converted to volumetric moisture content using values of bulk density from previous measurement and Equation 3.4 (Culley 1993).

3.3.6 Bulk Density of Wet Manure Pack and Compacted Manure Layer of the Dry Manure Pack Samples

Bulk density tests were conducted on twenty 50 mm lengths of undisturbed wet manure pack samples in a 75 mm diameter steel casing core. Samples were oven dried for 24 h at 65ºC and then weighed. The volume of the core was determined and the bulk density of the samples was then calculated according to the core method for determining bulk density as per Culley (1993).

The bulk density of the compacted manure layer of the dry manure pack was calculated according to the clod method for determining bulk density as per Culley (1993).

3.3.7 Volumetric Moisture Content of Wet Manure Pack Samples

Undisturbed wet manure pack cores of 50 mm length and 75 mm diameter were weighed, dried for one week at 65ºC, and then weighed again. The gravimetric and volumetric moisture contents of the manure samples were then determined using Equations 3.5 and 3.6.

The saturated volumetric moisture content of the wet manure pack at the feedlot was calculated based on the bulk density of the manure pack samples (as described in Section 3.3.6) and an assumed manure particle density of 100 kg/m^3 from Chen and Hruska (1983). The following equation from Culley (1993) was then used to calculate the saturated volumetric moisture content of the samples:

$$\theta_s = 1 - \frac{\rho_b}{\rho_p} \tag{3.9}$$

where:

θ_s = saturated volumetric moisture content (m^3/m^3)

ρ_b = bulk density (kg/m^3)

ρ_p = particle density (kg/m^3)

3.3.8 Drainage Characteristics of Wet Manure Pack Samples

Due to the fact that the wet manure pack was partially composed of organic material such as straw, the manure samples could not be subjected to a suction of 33 kPa on the pressure plate extractor to obtain field capacity. A good seal must be made between the pressure plate and the sample, and in the case of the wet manure samples, the straw made it difficult to obtain a proper seal in order to conduct the field capacity tests. Instead, a much smaller suction (20 cm, or 1.76 kPa) was used to determine the amount of moisture remaining in the wet manure pack samples at field capacity. Measurements were conducted on undisturbed 100 and 200 mm long wet manure pack cores.

The drainage characteristics of the wet manure pack samples were then determined from the following procedure: the manure cores (of 100 and 200 mm length as contained in its steel sampling sleeve) had plastic wrap placed over the top to prevent evaporation of water and nylon mesh placed over the bottom to prevent loss of material. The core was weighed and then placed in a water bath for 48 h to saturate. The water level in the bath was kept at a constant depth for the entire 48 hour period (75 mm for the 100 mm length cores and 150 mm for the 200 mm length cores). Finally, the core was removed from water bath, weighed, and placed on a layer of sand (to obtain a seal between the core and the sand) a suction of 20 cm for seven days. The saturated and equilibrium volumetric moisture content of the manure samples was then determined using Equation 3.6.

3.3.9 Volumetric Moisture Content of Granular Layer of the Dry Manure Pack Samples

Five granular layer samples of the dry manure pack taken from each pen were placed in aluminum tins, weighed, then dried for 24 h at 65ºC and weighed again. Fifty mm increments on a 75 mm diameter, 300 mm height clear PVC column were marked and nylon mesh was wrapped around the base. The PVC column and mesh were then weighed. The sample was then "poured" into the column to between 70 and 95 mm height, tapping the sides to settle the sample.

The column, sample, and nylon mesh were then weighed and plastic wrap loosely placed over the top of the column to prevent evaporation of water, but to allow expulsion of air. The column was placed in a water bath for 48 h to saturate and the water level in the bath was kept at a constant depth of 50 mm for the entire 48 h period. Finally, the column was then removed from water bath, allowed to drain for 10 s, and weighed again. The initial and saturated volumetric moisture content was then determined using Equation 3.6.

3.3.10 Saturated Hydraulic Conductivity of Wet Manure Pack Samples

The saturated hydraulic conductivity of the wet manure pack and the manure/soil interface samples was measured in the laboratory using the falling head method on undisturbed samples. The undisturbed samples were taken with 75 mm diameter, 300 mm long steel cores that were cut on a band saw into 50 mm lengths. The surface that had been in contact with the band saw was then “roughened” with a box cutter to ensure that any manure pores were not sealed by the cutting. The manure in the cores was then placed in a water bath just covering the bottom of the sample for at least 24 h to ensure saturation and to expel air from the pores. A layer of nylon mesh was added on top and bottom to prevent loss of sample. The weight of the sample was then recorded (wet weight).

The saturated sample was connected through tubing filled with air-free distilled water to the selected stand-pipe tube which had been filled to slightly above the chosen starting head. For the start of the test, water was allowed to fall in the stand-pipe tube, and thence through the sample. The time required for it to pass the successive calibration marks on the tube was recorded. The tube was then refilled with water and the test repeated three more times for each sample.

For each replication of the test, it was ensured that the seals were regreased to prevent leakage, the four butterfly nuts tightened evenly, water leaks checked with bottom and top plugs in place, tubes fully inserted into the connectors on the plates, and all air bubbles removed from tube when refilling. Each replication was run for five min to stabilize before taking readings of the saturated hydraulic conductivity. The length of time taken for a certain drop in hydraulic head was then measured. Finally, the drop in water level within the tube over a measured time interval was used to calculate the saturated hydraulic conductivity.

The hydraulic conductivity of the samples was calculated using the following equation (Jury et al. 1991):

$$K = \left[\frac{A_1 L}{A_2 (t_2 - t_1)}\right]^{\ln\left(h_1/h_2\right)} \tag{3.10}$$

where:

K = hydraulic head in cm/s

A_1 = area of tube (πr^2) in cm^2

A_2 = area of soil sample (cm^2)

t_2-t_1 = elapsed time (s)

h_1 = value of hydraulic head at t_1 (cm)

h_2 = value of hydraulic head at t_2 (cm)

L = length of soil sample (cm)

3.3.11 Saturated Hydraulic Conductivity of the Compacted Manure Layer of the Dry Manure Pack, 0-50 mm, and 50-100 mm Soil Samples

Lab hydraulic conductivity tests for the compacted manure layer of the dry manure pack and undisturbed soil samples were conducted on clods of the compacted manure layer of the dry manure pack and/or soil held in a PVC cylinder wax mold. The sample was placed in a PVC ring and the void area surrounding the sample was filled with wax. The wax was left to air dry for 24 h and then the wax, PVC, and sample were weighed (dry weight).

The samples were placed in a water bath for 24 h to saturate and then subjected to a falling head permeameter test as described in Section 3.3.9. Each sample had three replications. The cross-sectional area was calculated by measuring the length and width of the sample and the saturated hydraulic conductivity of the sample was calculated using Equation 3.9.

3.3.12 Deep Drainage (Recharge)

Changes in values for volumetric moisture content for soil depths of 0.6 to 1.2 m, as measured by TDR probes in the feedlot pens, were used to determine if drainage from excess moisture occurred at the River Ridge feedlot. The initial and final volumetric moisture contents of the soil were used at depths from 0.6 to 1.2 m in 200 mm increments, along with the field capacity of determined for the soil at 400-450 mm depth, to calculate the potential for drainage based on the change in soil moisture content with each depth increment. If the initial soil moisture was above that of field capacity, it was assumed that any following decrease in moisture was excess and it moved downward through the soil profile. If the soil moisture was at or below field capacity, it was assumed that there was little potential for movement of soil moisture, and thus, no drainage occurred, given a following decrease in moisture.

3.4 Analytical Methods

3.4.1 Characteristics of the Soil and Manure Pack

Physical and chemical characteristics of the soil and manure pack from the River Ridge feedlot were determined. Two pens at the River Ridge feedlot were investigated. By the start of the monitoring period, pen 6 had cattle in it for less than a year, while pen 4 had been operating for 6 years. Due to this disparity in age between the pens, physical properties of the manure/soil interface and hydrological characteristics such as measured hydraulic conductivity and drainage could be different and needed to be examined further.

A statistical analysis of the differences in physical and hydrological characteristics of pens 4 and 6 was required, as it was necessary to determine whether or not the differences between pens would affect the runoff modeling and water balance. An unpaired t-test available in Microsoft Excel (set to a probability of 0.05) was performed on texture, saturated hydraulic conductivity, and bulk density to determine if the two pens were significantly different.

Statistical analysis was not performed on physical parameters such as initial and saturated volumetric moisture content, as it became evident from the literature review that the main controlling factors for runoff and infiltration were soil texture, bulk density, and saturated hydraulic conductivity (Section 2.3.2). In addition, properties such as changes in moisture content are controlled by the texture and bulk density of the soil, thus another statistical test was deemed unnecessary.

3.4.2 Overall Water Balance Equation

The water balance equation for a feedlot pen, adapted from Gee and Hillel (1988) is described as follows:

$$AE = P1 + P2 - D - R - \Delta S - \Delta MP \tag{3.11}$$

where:

AE = actual evapotranspiration (mm)

P1 = precipitation (mm)

P2 = cattle moisture inputs (mm)

D = recharge or deep drainage below 0.6 m soil depth (mm)

ΔS = change in soil moisture storage in the top 0.6 m of soil (mm)

ΔMP = change in manure pack moisture storage (mm)
R = runoff (mm)

Each parameter was determined for use in this equation and an overall soil water balance performed for the study period, September 2003 to August 2004. Actual evaporation was determined by difference method from the other water balance parameters.

3.4.3 Potential Evapotranspiration

An estimate of potential evaporation was required for the soil water balance at the River Ridge feedlot as a reference for actual evaporation. Two equations were used in development of the daily water balance model, the ASCE standardized reference evapotranspiration equation (ASCE 2002) and the Hargreaves evapotranspiration equation (Hargreaves 1994), depending on the available meteorological data.

3.4.3.1 Standardized Reference Determination of Daily Evapotranspiration

Potential evapotranspiration was determined from measurement of meteorological parameters such as solar radiation, wind, relative humidity, and temperature with an equipped meteorological station on-site. Determination of daily evapotranspiration was completed using the following ASCE standardized reference evapotranspiration equation (ASCE 2002) for a well watered short crop surface (ETsz):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3.12}$$

where:
ET_o = reference evapotranspiration (mm/day)
R_n = net radiation at the crop surface (MJ m^{-2} day^{-1})
G = soil heat flux density (MJ m^{-2} day^{-1})
T = mean daily air temperature (°C)
u_2 = wind speed at 2 m height (m/s)
e_s = saturation vapour pressure (kPa)
e_a = actual vapour pressure (kPa)
$e_s - e_a$ = saturation vapour pressure deficit (kPa)

Δ = slope of the vapour pressure curve (kPa/°C)

γ = psychrometric constant (kPa/°C), 0.067 kPa/°C

Determination of daily potential evapotranspiration at the River Ridge feedlot was made according to Equation 3.9. ASCE (2002) also recommended an albedo of 0.25 and G was set at 0 MJ/m^{2}day. This equation is based upon the Penman-Monteith equation (Monteith 1985) and allows for estimation of water loss from a freely evaporating crop or soil surface in which evaporation is not limited by physical properties of the plant or the soil. It enables an estimation of evapotranspiration, given the measurement of relative humidity, wind, and temperature at only one level, usually at 2 m above the ground.

Droogers and Allen (2002) found that the standardized reference equation (ETsz) has many advantages over other methods, including the fact that it can be used worldwide without the need to estimate additional parameters. In addition, the method is well documented and has been implemented into a wide variety of software.

3.4.3.2 Hargreaves Determination of Daily and Monthly Evapotranspiration

The Hargreaves equation (Hargreaves 1994) was also used for determination of daily and monthly potential evapotranspiration when only limited meteorological data for a site is available (eg. only temperature and location). The equation is as follows:

$$ET = \left[(0.0023 \bullet 0.408 \bullet RA) \bullet (T_{avg} + 17.8)\right] \bullet \sqrt{TD} \tag{3.13}$$

where:

ET = evapotranspiration (mm/day)

T_{avg} = average daily temperature (ºC), defined as (T_{max} + T_{min})/2

T_{max} = maxiumum daily temperature (ºC)

T_{min} = minimum daily temperature (ºC)

RA = extraterrestrial solar radiation (MJ m^{-2} d^{-1})

TD = daily temperature range (ºC), T_{max} - T_{min}

Hargreaves (1994) developed an expression for potential evapotranspiration in terms of mean air temperature and extraterrestrial radiation. If extraterrestrial solar radiation data is not available for a particular site, it can be obtained from tables and/or a set of calculations from Hargreaves (1994), based on latitude and Julian day.

The Hargreaves equation is useful under limited meteorological data, as extraterrestrial solar radiation can be calculated from equations or tables according to Hargreaves (1994). Droogers and Allen (2002) compared the accuracy of both the standardized reference equation and the Hargreaves equation for potential evapotranspiration and found good agreement between the two methods. In addition, they also stated that standardized reference equation is one of the most accurate, but requires large amounts of meteorological data.

3.4.4 Runoff Modelling

Two models for rain, the Green-Ampt runoff equation and the USDA rainfall-runoff equation, and one for snowmelt into frozen soils were used to provide runoff estimation for the feedlot water balance. This goal was accomplished by comparing modeled runoff to measured actual runoff events (or lack thereof) and measured rainfall simulation runoff for both the scraped soil surface and manure pack. Both the Green-Ampt and USDA SCS models are classically used for engineering and hydrological representation and are based upon that of physically based concepts of infiltration and runoff and measurement of field parameters (Lane et al. 1983).

A determination as to which model was the most appropriate for use in the overall water balance of the feedlot was made based on several factors, including the comparison between measured and modeled runoff data, the precipitation data that was available for the River Ridge feedlot, and finally an assessment of which model is most commonly used for determining runoff at feedlots.

3.4.4.1 Green-Ampt Runoff Model

The Green-Ampt model (Equations 2.2, 2.3 and 2.4) requires soil saturated hydraulic conductivity, initial and saturated volumetric soil moisture contents, rainfall intensity, and soil water suction at the wetting front (approximate air-entry value) as input parameters. The model is physically based upon Darcy's equation and assumes the development of a sharp wetting front in a homogeneous soil (although it can be modified for layered systems). Advantages of this model are that it is physically based and once a set of solutions is found, the model can be run for the same soil for various rainfall intensities.

3.4.4.2 The USDA Soil Conservation Service Runoff Model

The USDA runoff estimation method (Equation 2.5) incorporates the Soil Conservation Service (SCS) Curve Number model (USDA 1973) (Equation 2.6). It was used to obtain an estimate of runoff from the scraped soil surface and manure pack at the River Ridge feedlot

3.4.4.3 Snowmelt Runoff Estimation Equation

Snowmelt on frozen soils can produce large volumes of water as infiltration is very low due to the presence of ice blocking soil pores. These findings are irrespective of texture and are a function of frozen soil moisture content.

No modifications were made to the equation for manure pack surface (Equation 2.7). This is due to the fact that during the monitoring period (September 2003 to August 2004), there were no cattle in the pens, resulting in a smooth pen surface. Therefore, little surface storage of snowmelt would occur.

4. RESULTS AND DISCUSSION

The goal of this section is to present the results and discussion of measurements collected by field and laboratory experiments at the River Ridge feedlot. Analysis of each of the water balance parameters will be discussed in separate sections and the rationale for using measurements from each pen, supplemental data, and/or data from current literature will also be discussed. A summary and analysis of the water balance of an inactive feedlot pen will also be presented.

4.1 Characteristics of the Soil and Manure Pack

Physical and chemical characteristics of the soil and manure pack in two feedlot pens were determined. Due to a disparity in age between the pens (less than one year versus over six years), physical properties of the manure/soil interface and hydrological characteristics such as measured hydraulic conductivity and drainage could be different and thus were investigated separately.

A statistical analysis of the differences in physical and hydrological characteristics of pens 4 and 6 was performed, as it was necessary to determine whether or not the differences between pens affected the runoff modeling and water balance. A t test set to a probability of 0.05 was performed on texture, saturated hydraulic conductivity, and bulk density to determine if the two pens were significantly different. A statistical analysis was not performed on the initial and saturated volumetric moisture contents, as these properties are controlled by texture and bulk density.

4.1.1 Soil

4.1.1.1 Texture

Soil texture in the top 0.6 m of the feedlot pens was between 14 and 24% clay content and 42 to 60% sand content (Table 4.1). The soil texture is classified as ML (inorganic silts, slight to no plasticity) to CI (clay of intermediate plasticity) using the

ASTM classification system (PFRA 2002) or loam using the USDA soil textural triangle (USDA textural triangle).

Table 4.1. Clay and sand content of feedlot pens 4 and 6 at the River Ridge feedlot.

Depth	Clay (%)		Sand (%)	
	Pen 4	Pen 6	Pen 4	Pen 6
0-100 mm	17 (1.7)	16 (4.1)	49 (6.6)	54 (8.2)
100-200 mm	14 (0.9)	16 (5.8)	54 (2.0)	57 (9.0)
200-400 mm	15 (NA)	17 (2.7)	55 (NA)	51 (7.8)
400-600 mm	16 (NA)	24(5.0)	60 (NA)	42 (7.6)

All values for clay and sand content for each pen are average values, numbers in brackets are standard deviation. Number of samples: 0-100 mm depth (6 from pen 4, 6 from pen 6), 100-200 mm depth (4 from pen 4, 6 from pen 6), 200-400 mm depth (2 from pen 4, 6 from pen 6), and 400-600 mm depth (2 from pen 4, 6 from pen 6). NA: Standard deviation not available for two values.

Performance of a t-test on the texture values revealed no significant difference between pens 4 and 6 for all depths. As a result, values at each depth increment were combined as an average for further calculations. A statistical analysis was not performed on the samples at the 400-600 mm depth increment, due to the fact that only two samples were taken in pen 4.

4.1.1.2 Chemical Analysis

Carbon analysis of the soil samples from the 0-50 mm depth revealed an average organic carbon and total carbon content of 0.59 and 2.01%, respectively (Table 4.2).

Table 4.2. Chemical analysis of soil samples from 0-50 mm depth.

	Organic Carbon (%)	Total Carbon (%)
Pen 4, Sample 1	0.79	2.00
Pen 4, Sample 2	0.22	1.86
Pen 6, Sample 1	1.19	2.53
Pen 6, Sample 1	0.17	1.64
Average (σ)	0.59 (0.48)	2.01 (0.38)

The organic carbon content within each pen, as well as between the two pens, varies greatly. The total carbon content between pens 4 and 6 has similar values. The organic matter content of the top 50 mm of soil was calculated to be 1.2% (Equation 3.8) at the River Ridge feedlot. In line with these findings, Kennedy et al. (1999) reported that the organic matter content of the surface soil just below the manure/soil interface was 1.5%.

4.1.1.3 Saturated Hydraulic Conductivity

The arithmetic average saturated hydraulic conductivity, measured with a falling head permeameter for soil under the compacted manure layer (0 – 450 mm depth), ranged from 2.0×10^{-6} cm/s at the manure/soil interface, to 3.9×10^{-5} cm/s at the 200-250 mm depth (Figure 4.1 and Table 4.3).

Table 4.3. Average saturated hydraulic conductivity (Ks) of the manure pack and soil at the River Ridge feedlot.

	Ks (cm/s x 10^{-5})		
	Pen 4	Pen 6	Average
Dry Manure Pack			
Granular manure layer	NA	NA	NA
Compacted manure layer	2.3 (3.0)	0.11(0.20)	0.63(2.7)
0-50 mm soil	0.49 (9.4)	0.55 (8.2)	0.51(8.5)
50-100 mm soil	8.5 (130)	0.56 (0.52)	3.4 (120)
200-250 mm soil	3.6 (3.1)	4.9 (1.4)	3.9 (10)
400-450 mm soil	2.4 (8.8)	5.2 (2.8)	2.3 (6.9)
Wet Manure Pack			
0-100 mm Wet MP	190 (160)	12 (300)	48 (220)
100-200 mm Wet MP	200 (NA)	NA	21 (NA)
MSI	0.37 (NA)	0.10 (NA)	0.20 (NA)
Soil under MSI	0.69 (5.0)	3.5 (2.7)	1.5 (2.4)

All values for saturated hydraulic conductivity are averages of the log of Ks, and numbers in brackets are standard deviations. Compacted manure layer: compacted manure layer of the dry manure pack (60 mm), Wet MP: wet manure pack (~50 mm), 0-50 mm soil: soil at 0-50 mm depth under the compacted manure layer of the dry manure pack, MSI: manure/soil interface beneath the wet manure pack (50 mm core including manure above and soil below), Soil under MSI: soil samples taken beneath the cores incorporating the manure soil interface (not the surface soil directly underlying the manure/soil interface), Ks: saturated hydraulic conductivity, NA: data not available. Each saturated hydraulic conductivity value was an average of 4 replications run on each sample. Number of samples: 0-50 mm depth (6 from pen 4, 4 from pen 6), 50-100 mm depth (4 from pen 4, 2 from pen 6), 200-250 mm depth (5 from pen 4, 5 from pen 6), and 400-450 mm depth (5 from pen 4, 3 from pen 6), Manure/soil interface (2 from pen 4, 2 from pen 6), compacted manure layer (4 from pen 4, 3 from pen 6), granular layer of the dry manure pack (6 in pen 4, 4 in pen 6), wet manure pack 0-100 mm (3 from pen 4, 4 from pen 6), wet manure pack 100-200 mm (2 from pen 4, 1 from pen 6).

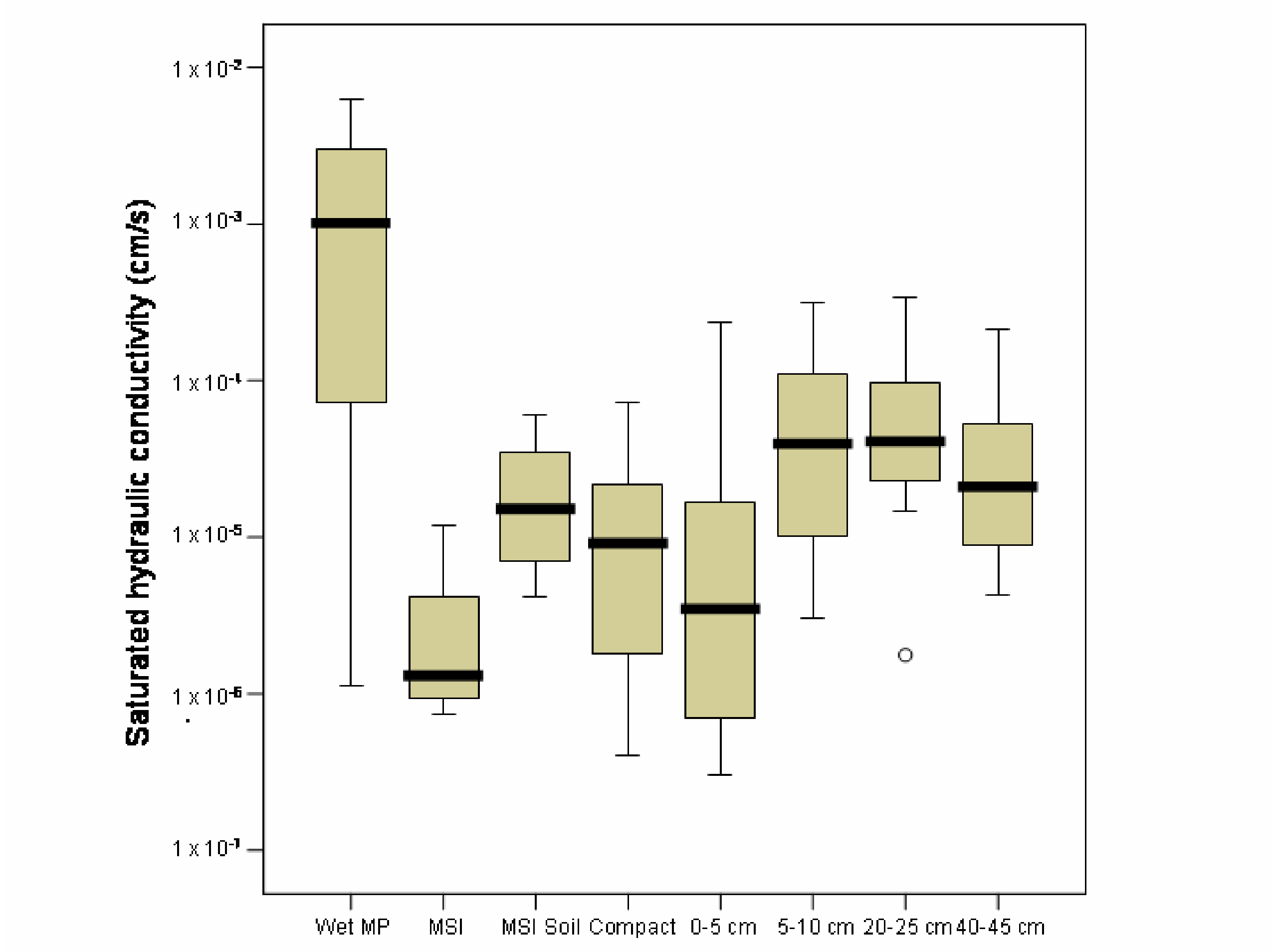

Figure 4.1. Box plot of saturated hydraulic conductivity of feedlot soil and manure samples (pens 4 and 6).

Wet MP: wet manure pack, MSI: manure/soil interface beneath the wet manure pack (50 mm core including manure above and soil below), MSI Soil: soil samples taken beneath the cores incorporating the manure soil interface (not the surface soil underlying the manure/soil interface), Compact: Compacted manure layer of the dry manure pack, 0-50 mm soil: soil at 0-50 mm depth under the compacted manure layer of the dry manure pack. Each saturated hydraulic conductivity value was an average of 4 replications run on each sample. The black bar is the average value for the sample set, box is the standard deviation for the sample set, the whiskers are the 75% and 25% quartile values, and the dots are outlier values. Number of samples: listed in Table 4.3.

Performance of a t-test on the saturated hydraulic conductivity values revealed no significant difference between pens 4 and 6 for all depths. As a result, values at each depth increment were combined as an average for further calculations.

McCullough et al. (2001) also measured the hydraulic conductivity of a new sandy loam feedlot surface in Texas in the laboratory with a constant and falling head permeameter. It was reported that soil samples taken from the feedlot floor before the introduction of cattle had a saturated hydraulic conductivity ranging from 9.3 x 10^{-6} to 1.8 x 10^{-5} cm/s, while samples taken after nine months of stocking ranged from 5.3 x 10^{-7} to 1.9 x 10^{-6} cm/s. The after-stocking values are the same order of magnitude as the River Ridge manure/soil interface samples underlying the wet manure pack (2.0 x 10^{-6} cm/s, Table 4.3). This makes sense due to the fact that once the feedlot was stocked with cattle, a manure/soil interface would develop between the manure pack and the underlying soil, causing the hydraulic conductivity to decrease by an order of magnitude.

The lowest saturated hydraulic conductivity, by an order of magnitude, was found at the 0-50 mm depth, whereas the highest saturated hydraulic conductivity was at 200-250 mm (Table 4.3). It is possible that there were salts and/or organic matter in the 0-50 mm depth causing the low saturated hydraulic conductivity values. In agreement with this statement, Kennedy et al. (1999) noted that sodium salts in excess of calcium and potassium in the manure/soil interface layer tends to disperse soil in the layer and reduce the infiltration capacity.

4.1.1.4 Bulk Density

The average bulk density of the soil underlying the dry manure pack ranged from 1290 kg/m^3 for the 200-250 mm depth to 1770 kg/m^3 for the 50-100 mm depth (Table 4.4 and Figure 4.2).

Table 4.4. Average bulk density of the manure pack and soil at the River Ridge feedlot.

	Bulk density (kg/m^3)		
	Pen 4	Pen 6	Average
Dry Manure Pack			
Granular manure layer	460 (110)	410 (140)	440 (120)
Compacted manure layer	760 (140)	810 (90)	780 (110)
0-50 mm soil	1580 (200)	1770 (60)	1650 (180)
50-100 mm soil	1690 (170)	1650 (140)	1680 (150)
200-250 mm soil	1410 (40)	1290 (260)	1350 (190)
400-450 mm soil	1490 (50)	1470 (30)	1490 (50)
Wet Manure Pack			
0-100 mm Wet MP	220 (30)	260 (120)	240 (90)
100-200 mm Wet MP	220 (NA)	NA	230 (NA)
MSI	1050 (NA)	810 (NA)	930 (NA)
Soil under MSI	1470 (10)	1460 (60)	1460 (30)

All values for bulk density are average values, and numbers in brackets are standard deviations. BD: dry bulk density, NA: data not available. Number of samples and notes: listed in Table 4.3.

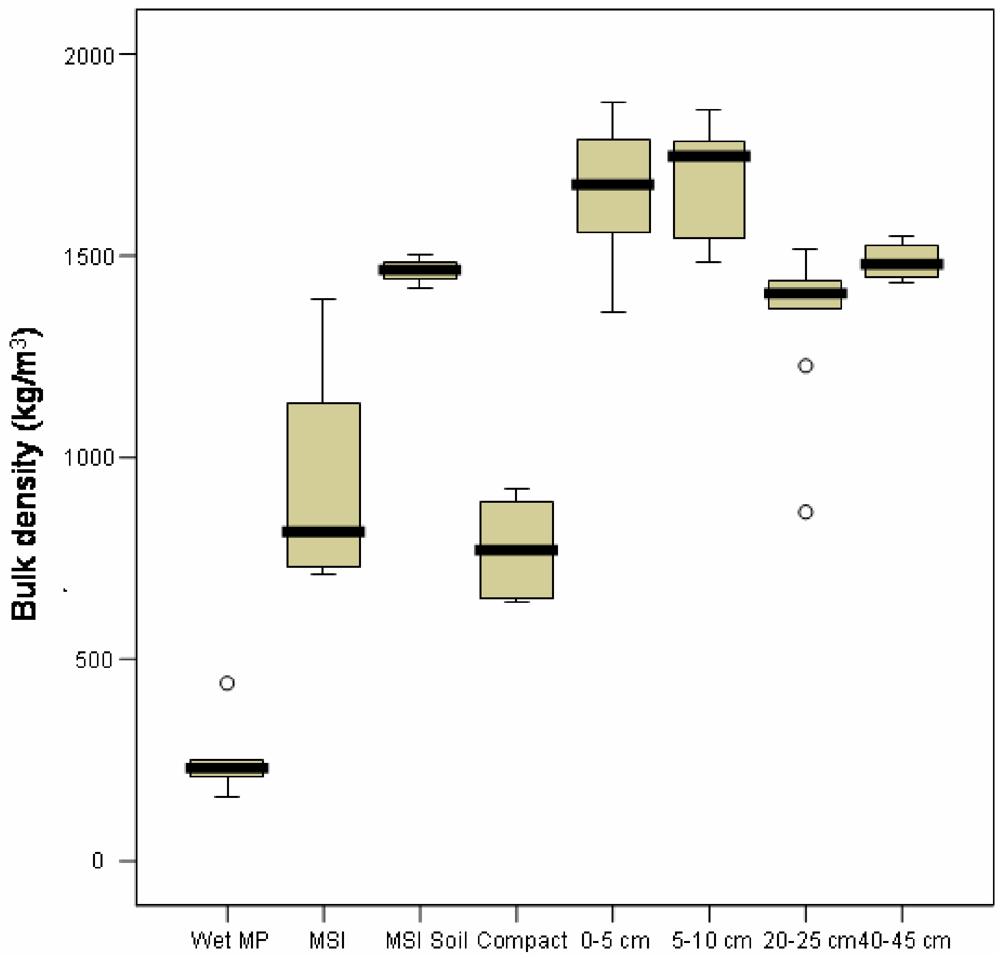

Figure 4.2. Box plot of bulk density of feedlot soil and manure samples (pens 4 & 6). Wet MP: wet manure pack, MSI: manure/soil interface beneath the wet manure pack (50 mm core including manure above and soil below), MSI Soil: soil samples taken beneath the cores incorporating the manure soil interface (not the surface soil underlying the manure/soil interface), Compact: Compacted manure layer of the dry manure pack, 0-50 mm soil: soil at 0-50 mm depth under the compacted manure layer of the dry manure pack. The black bar is the average value for the sample set, box is the standard deviation for the sample set, the whiskers are the 75% and 25% quartile values, and the dots are outlier values. Number of samples: listed in Table 4.3.

Performance of a t-test on the bulk density values at each depth revealed no significant difference at P=0.05 between pens 4 and 6 for all depths. As a result, values at each depth increment were combined as an average for further calculations.

The River Ridge feedlot soil samples revealed a higher bulk density for the top 100 mm of soil, relative to the 200-250 mm depth. This indicated that hoof action from the cattle in the pens caused significant compaction of the underlying soil. Miller et al. (2003) also noted that bulk density was highest where cattle traffic was greatest.

4.1.1.5 Initial and Saturated Volumetric Moisture Content

At sampling time (September 2003), the average initial moisture content of the soil from 0-50 and 400-450 mm depths underlying the compacted manure layer ranged from 0.15 to 0.21 m^3/m^3 (Table 4.5 and Figure 4.3).

Table 4.5. Initial and saturated volumetric moisture contents for the River Ridge feedlot.

	θ_i (m^3/m^3)	θ_s (m^3/m^3)
Dry Manure Pack		
Granular manure layer	0.01 (0.00)	0.82 (0.08)
Compacted manure layer	0.25 (0.09)	0.44 (0.12)
0-50 mm soil	0.21 (0.03)	0.31 (0.04)
50-100 mm soil	0.19 (0.03)	0.39 (0.07)
200-250 mm soil	0.15 (0.02)	0.47 (0.06)
400-450 mm soil	0.21 (0.03)	0.44 (0.06)
Wet Manure Pack		
0-100 mm Wet MP	0.46 (0.14)	0.75 (0.03)
100-200 mm Wet MP	0.52 (NA)	0.78 (0.01)
MSI	0.46 (NA)	NA
Soil under MSI	0.24 (0.04)	NA

All values are average values and numbers in brackets are standard deviations, θ_i: Initial volumetric moisture content at time of sampling (Sept. 2003), θ_s: saturated volumetric moisture content. θ_s for the wet manure pack was estimated based on a manure particle density of 100 kg/m^3 (Chen and Hruska, 1983) and bulk densities from Table 4.4. NA: Data not available. Compacted manure layer: compacted manure layer of the dry manure pack (60 mm), Wet MP: wet manure pack (~50 mm), 0-50 mm soil: soil at 0-50 mm depth under the compacted manure layer of the dry manure pack, MSI: manure/soil interface beneath the wet manure pack (50 mm core including manure above and soil below), Soil under MSI: soil samples taken beneath the cores incorporating the manure soil interface (not the surface soil underlying the manure/soil interface), Number of samples same as listed in Table 4.3.

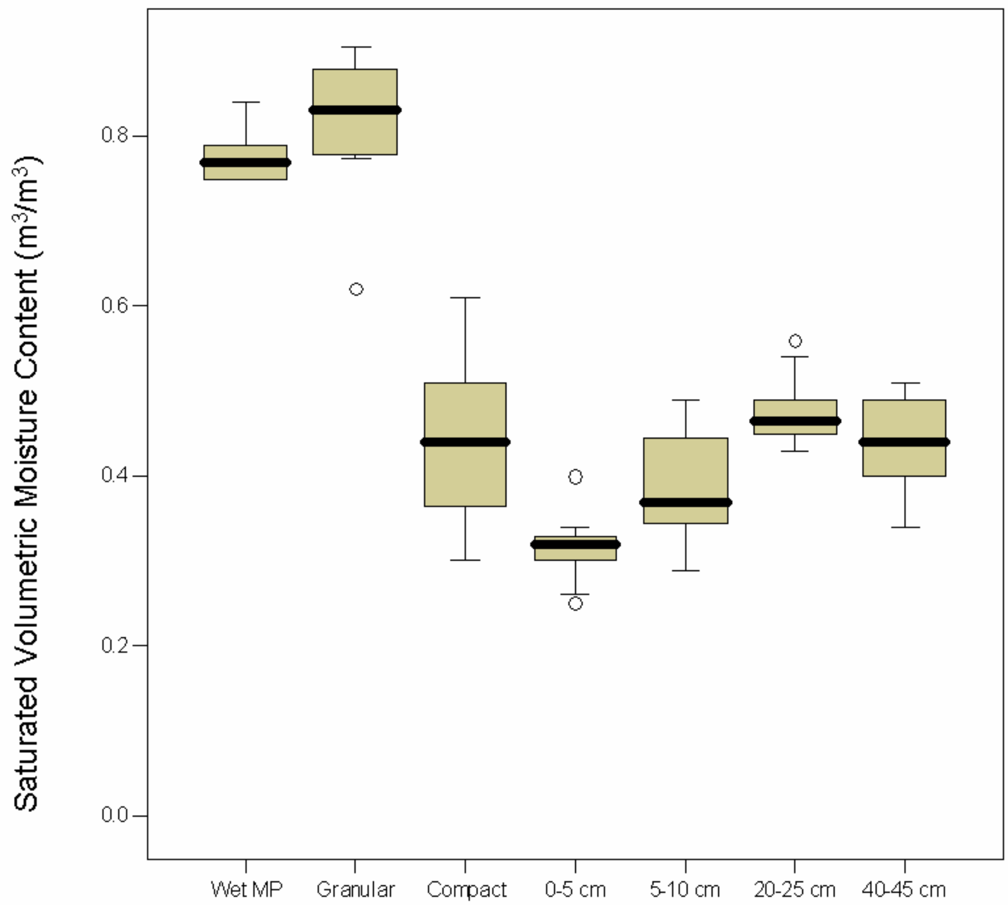

Figure 4.3. Box plot of saturated volumetric moisture content of feedlot soil and manure samples (pens 4 and 6).

Granular: Granular manure layer of the dry manure pack, Compact: Compacted manure layer of the dry manure pack, 0-50 mm soil: soil at 0-50 mm depth under the compacted manure layer of the dry manure pack. The black bar is the average value for the sample set, box is the standard deviation for the sample set, the whiskers are the 75% and 25% quartile values, and the dots are outlier values. Number of samples: listed in Table 4.3.

The average initial moisture content of the soil underlying the manure/soil interface (and wet manure pack) was 0.24 m^3/m^3. The saturated volumetric moisture content for soil increments between 0 and 450 mm depths ranged from 0.31 to 0.47 m^3/m^3 (Table 4.5)

4.1.2 Wet Manure Pack and Manure/Soil Interface

At the time of wet manure pack sampling (August 2003), there were cattle present in pen 4, but not in pen 6. The wet manure pack samples from both pens were taken from the manure mound areas of the pen (with the deepest wet manure pack) and contained varying amounts of straw used as bedding during the winter. The wet manure pack characteristics in Table 4.3, Table 4.4, Figure 4.1, and Figure 4.2

represent samples taken in August 2003 for both pens 4 and 6. The wet manure pack thicknesses at this time ranged from 300 to 500 mm for pen 4 and 250 to 450 mm for pen 6.

The values for bulk density of the wet manure pack for the 0-100 mm depth ranged from 220 kg/m^3 to 260 kg/m^3 (Table 4.4). The bulk density of the wet manure pack (Table 4.4) was 230 kg/m^3 for the 100-200 mm depth. The initial and saturated moisture content of the 0-100 mm depth of the wet manure pack was 0.46 m^3/m^3 and 0.75 m^3/m^3, respectively (Table 4.5), and that of the 100-200 mm depth was 0.52 m^3/m^3 and 0.78 m^3/m^3, respectively (Table 4.5).

A manure/soil interface was identified at the River Ridge feedlot as a thin black line between the base of the manure pack and the surface of the soil layer. The manure/soil interface was approximately 2 mm in thickness (from visual observation). The initial volumetric moisture content of the manure/soil interface (0.46 m^3/m^3, Table 4.5) was similar to that of the wet manure pack 0.46 m^3/m^3 and 0.52 m^3/m^3, respectively, for 0-100 and 100-200 mm depths (Table 4.5), rather than that of the underlying soil (0.24 m^3/m^3, Table 4.5).

The saturated hydraulic conductivity of the wet manure pack (both 0-100 mm and 100-200 mm depth) was one to three orders of magnitude higher than that of the samples containing the manure/soil interface (Table 4.3). This was attributed to the fact that the development of a manure/soil interface, as well as compaction of the soil surface from cattle hoof action, restricts water movement into the underlying soil.

The saturated hydraulic conductivity for the samples containing the manure/soil interface was an order of magnitude less than that of the soil beneath (Table 4.3).

4.1.3 Dry Manure Pack

The compacted manure layer of the dry manure pack was likely formed when the bottom 50-100 mm of wet manure pack, sitting above the manure/soil interface on the pen floor, dried out. This is the part of the wet manure pack that would be the most compacted due to cattle traffic within the pen.

The dry manure pack (including the granular manure layer, as well as the compacted manure layer) characteristics in Table 4.3, Table 4.4, Figure 4.1 and Figure 4.2 represent samples taken in September of 2003 from both pens 4 and 6. Upon sampling in September of 2003, the average height of the granular layer of the dry manure pack in pen 4 was 57 mm (with a standard deviation of 7.5 mm) and that of pen 6 was 68 mm (with a standard deviation of 5.6 mm). An average depth of 63 mm was used for further calculations involving the dry manure pack.

The granular manure layer of the dry manure pack had average initial and saturated volumetric moisture contents of 0.01 and 0.82 m^3/m^3, respectively (Table 4.5). It should also be noted that the bulk density of the granular layer of the dry manure pack decreased with saturation (from 440 to 340 kg/m^3), while the volume increased, on average, by 23%.

The overall thickness of the compacted manure layer of the dry manure pack in both pens was approximately 50 mm. Most of the measurements conducted and samples taken from the feedlot pens during the study period (September 2003 to August 2004) were of this type of manure material. The compacted manure layer of the dry manure pack had average initial and saturated volumetric moisture contents of 0.25 and 0.44 m^3/m^3, respectively (Table 4.5).

The saturated hydraulic conductivity for the soil at 0-50 mm depth (5.1×10^{-6} cm/s, Table 4.3) is of the same order of magnitude as that for the compacted manure layer (6.3×10^{-6} cm/s, Table 4.3), as well as the manure/soil interface (2.0×10^{-6} cm/s, Table 4.3).

There are no other known studies with which to compare or discuss the properties of the granular layer and compacted manure layer of the dry manure pack at the River Ridge feedlot. As a result, properties of the compacted manure layer were compared to those of the wet manure pack at the River Ridge feedlot. In doing this comparison, the saturated hydraulic conductivity of the compacted manure pack was one to three orders of magnitude lower than the wet manure pack (both 0-100 mm and 100-200 mm depth, Table 4.3).

4.1.4 Moisture Retention Characteristics of the Soil and Granular Layer of the Dry Manure Pack

An assessment of field capacity was required in the water balance to determine the amount of drainage due to excess moisture at the River Ridge feedlot and water holding capacity of the manure pack (Table 4.6).

Table 4.6. Saturated and volumetric moisture retention values for soil and granular layer of the dry manure pack.

	θ_s (m^3/m^3)	Field capacity (33 kPa) (m^3/m^3)
0-50 mm soil	0.31 (0.04)	0.27 (0.04)
50-100 mm soil	0.39 (0.07)	0.28 (0.08)
200-250 mm soil	0.47 (0.06)	0.17 (0.05)
400-450 mm soil	0.44 (0.06)	0.24 (0.03)
Granular manure layer	0.82 (0.08)	0.44 (0.16)

θs: saturated volumetric moisture content, PWP: permanent wilting point, NA: data not available. Number of samples: 0-50 mm depth (7 from pen 4, 3 from pen 6), 50-100 mm depth (7 from pen 4, 5 from pen 6), 200-250 mm depth (7 from pen 4, 3 from pen 6), and 400-450 mm depth (7 from pen 4, 3 from pen 6), granular layer of the dry manure pack (5 in pen 4, 2 in pen 6). All values are average values and numbers in brackets are standard deviations.

The saturated volumetric moisture content of the soil from 0 to 450 mm depth ranged from 0.31 to 0.47 m^3/m^3. Volumetric moisture contents were calculated for each depth increment using bulk densities established from undisturbed cores (sampled in Sept. 2003), along with the gravimetric moisture contents from the pressure plate extractor (as described in Section 3.3.4). It was assumed that the disturbed soil samples taken in Sept. 2003 had the same bulk density as the undisturbed samples taken in Sept. 2003. The field capacity (based on moisture retention at 340 cm tension or 33 kPa) of the soil was measured to be between 0.17 and 0.28 m^3/m^3 and the permanent wilting point ranged from 0.11 to 0.14 m^3/m^3 (calculated from Equation 3.7).

The organic carbon content of the samples from depth increments below 0-50 mm depth was assumed to be negligible, as the topsoil was cleared away during pen construction.

The granular layer of the dry manure pack, which effectively becomes the wet manure pack upon saturation, had a field capacity (33 kPa on the soil pressure plate extractor, or 340 cm tension) of 0.44 m^3/m^3 (Table 4.6).

4.2. Measured Hydrological Components

4.2.1 Precipitation (P)

4.2.1.1 Measurement Methods and Long-Term Precipitation Values

The following three sources of data were used for determining long-term and monitoring period (September 2003 to August 2004) precipitation values: data collected with the meteorological station at the River Ridge feedlot, climatic normals from the town of Eston (Environment Canada 2004), and data from the town of Kindersley from 1911 until August 2004 (Environment Canada 2004). Monthly precipitation values were required for monthly comparisons, while daily and 30 min rain values were needed for daily runoff determination. Kindersley data (from Environment Canada 2004) was used for monthly and daily determination of precipitation for both long term (over 30 years) and the monitoring period (Sept. 2003 to Aug. 2004) to supplement missing data from the feedlot. Long-term Kindersley data was used for determination of the frequency of 24 h rain events, while long-term Saskatoon data from 1960 to 1992 (Environment Canada 2004) was used for determination of the amount and the return period of 30 min rain events.

The feedlot 30 min and 24 h data were used to assess the lack of runoff that occurred from the manure pack and the potential for runoff occurrence. The Eston meteorological station (from Environment Canada 2004) was used to confirm any long term differences between the region of the River Ridge feedlot and that of Kindersley, as it was closer to the feedlot than Kindersley, however it stopped collection of data in the year 2000, whereas the Kindersley station is still active.

Average annual precipitation for the Eston area (as obtained from 1971-2000 climate normals for Eston from Environment Canada 2004) shows 29 mm less precipitation as compared to long-term Kindersley data (Table 4.7). The warm season (April through October) for Kindersley in 2003 was wetter than normal (305 mm as opposed to 268 mm). Winter for 2003-04 (Nov through March) was much drier (33 mm) than normal (89 mm).

Table 4.7. Precipitation data for Kindersley and Eston from Environment Canada (2004).

Year	Annual Total (mm)	Winter (mm)	Warm season (mm)
1971-2000 Kindersley	326	89	268
2003-2004 Kindersley	338	33	305
1971-2000 Eston	297	74	224

Winter precipitation spans over two calendar years (ie. 2003 winter precipitation data includes Nov. and Dec. 2003 and Jan.-Mar. 2004), as the hydrological year is from Sept. 2003 to Aug. 2004. Winter months are those with the average air temperature < 0°C. Winter precipitation measurements are snowfall measurements converted into snow water equivalents. Warm season precipitation included Sept. and Oct. 2003 and Apr. through Aug. 2004.

Climatic records for Kindersley from 1911-2004 (from Environment Canada 2004) were examined for 24 h rainfall amounts during the warm months of April through September. The number of 24 h rainfall events at Kindersley in a one year period for various precipitation intervals were presented in Figure 4.4.

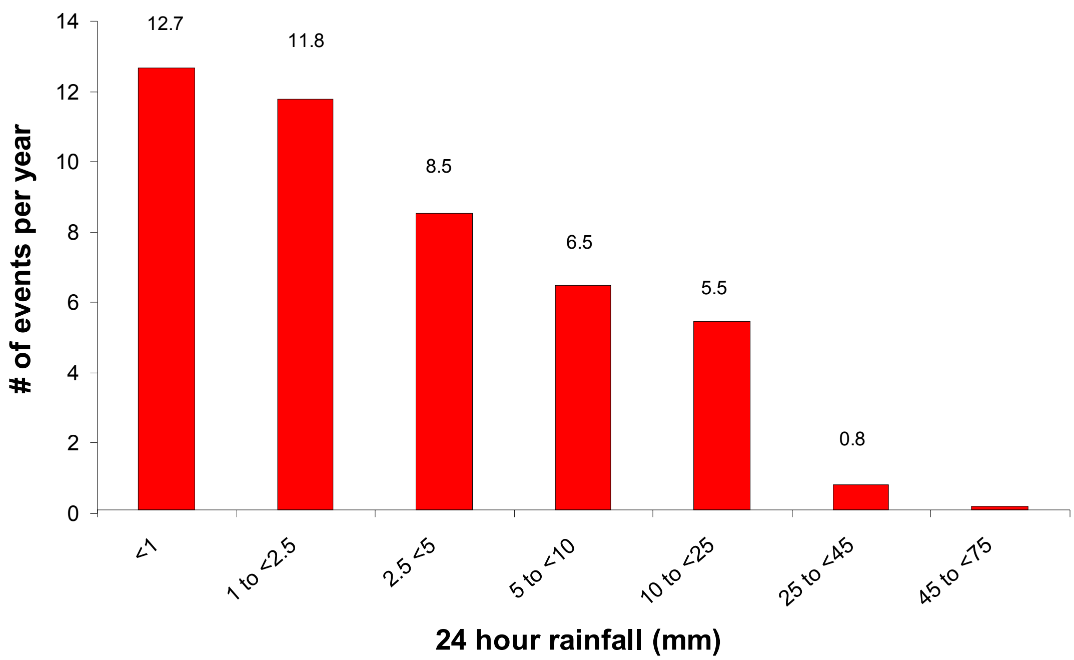

Figure 4.4. Frequency of daily rainfall at Kindersley in number of events per year (1911-2004, Environment Canada 2004).

From Figure 4.4, it can be expected that during a one year period 12.7 (24 h) events of less than 1 mm will occur and 0.8 events will occur of between 25 to 45 mm.

4.2.1.2 Precipitation Events Experienced at the River Ridge Feedlot Site

A total of 314.3 mm of rainfall occurred (with measured and missing data supplemented from Kindersley, Table 4.8) at the feedlot from September 1, 2003 to August 31, 2004, with 280.1 mm of that received during the warm season (Apr. to Oct.). The study year started off very dry (September 2003 had only 21.2 mm) and continued so until June, when 96.9 mm of precipitation was received.

Table 4.8. River Ridge feedlot rainfall, temperature, and potential evapotranspiration data including supplemental data from Kindersley (2003-04).

Month	Rainfall (mm rainfall)	Temperature (°C)	PET (mm)
Sept.	21.2	12.9	102.3
Oct.	7.0	-0.1	46.8
Nov.	1.5	-8.6	0
Dec.	2.0	-4.9	0
Jan.	19.4	-16.8	0
Feb.	3.6	-8.2	0
Mar.	7.7	10.0	0
Apr.	4.0	6.8	87.9
May	17.2	8.3	117.5
Jun.	96.9	14.5	129.5
July	62.0	18.8	147.4
Aug.	71.8	16.2	116.2
Apr. to Oct.	Total 280.1	Avg. 11.1	Total 748
Year	Total 314.3	Avg. 4.1	Total 748

Total warm: Total precipitation received through the months of Apr. to Oct., Avg. warm: average temperatures for the months of Apr. to Oct., PET: includes ETsz feedlot PET plus ETh Kindersley PET, NA: data is not available. The meteorological station at the feedlot site supplied the feedlot hydrological year data, Potential evapotranspiration values do not include winter months Nov thru March and were assumed to be zero.

The meteorological data for the feedlot during the warm season of the monitoring period was only about 57% complete (123 days out of 214), so 91 days of supplemental data was used from Environment Canada 2004 as collected from Kindersley during the monitoring period. Of the 91 days of supplemental Kindersley data, only 19 days experienced rainfall events. Since Eston and area (including the River Ridge feedlot) typically receives less precipitation (Table 4.7), long-term data from Eston as compared to Kindersley was used to determine the amount of correction for the supplemental precipitation data (Appendix A).

With the incorporation of Kindersley supplemental data (Environment Canada 2004), there were 37 (24 h) rainfall events of 0.1 to 5 mm at the feedlot and 39 at Kindersley (Figure 4.5). There were also 11 events of between 5 to 10 mm and 10 events of 10 to 50 mm.

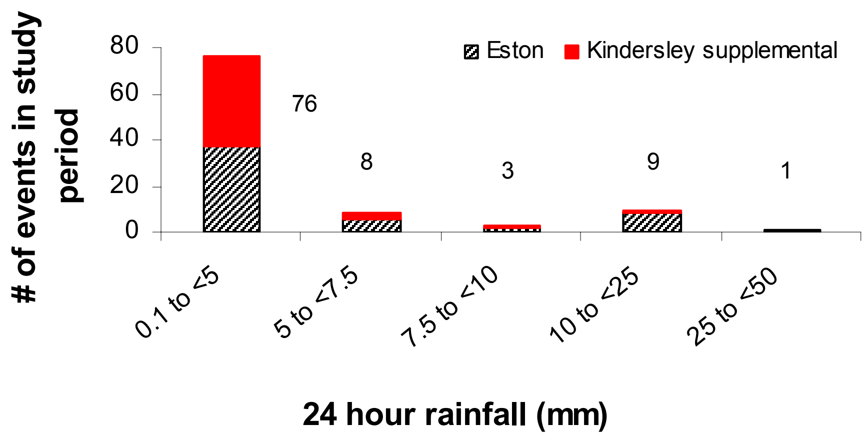

Figure 4.5. Number of 24 h rainfall events at feedlot during monitoring period (Sept. 2003 to Aug. 2004, including Kindersley supplemental data).

From long-term climatic data from Kindersley (Figure 4.4), 6.5 events of between 5 to 10 mm, 5.5 events of between 10 and 25 mm, and 0.8 events of between 25 to 45 mm would be expected to occur during a one year period, indicating that the number of equivalent 24 h events experienced at the River Ridge feedlot during the monitoring period was slightly above expected values (Figure 4.5).

The three greatest 24 h rainfall amounts measured by the meteorological station at the River Ridge feedlot during the monitoring period were 25.5 mm received on June 6th, 2004, 19.4 mm received on June 14th, and 19.3 mm received on August 7th, 2004 (Figure 4.6). In comparison, the two highest daily rainfall amounts during the monitoring period for the Kindersley supplemental data were 12.4 mm received on Aug. 23rd, 2004 and 9.2 mm received on May 5th, 2004.

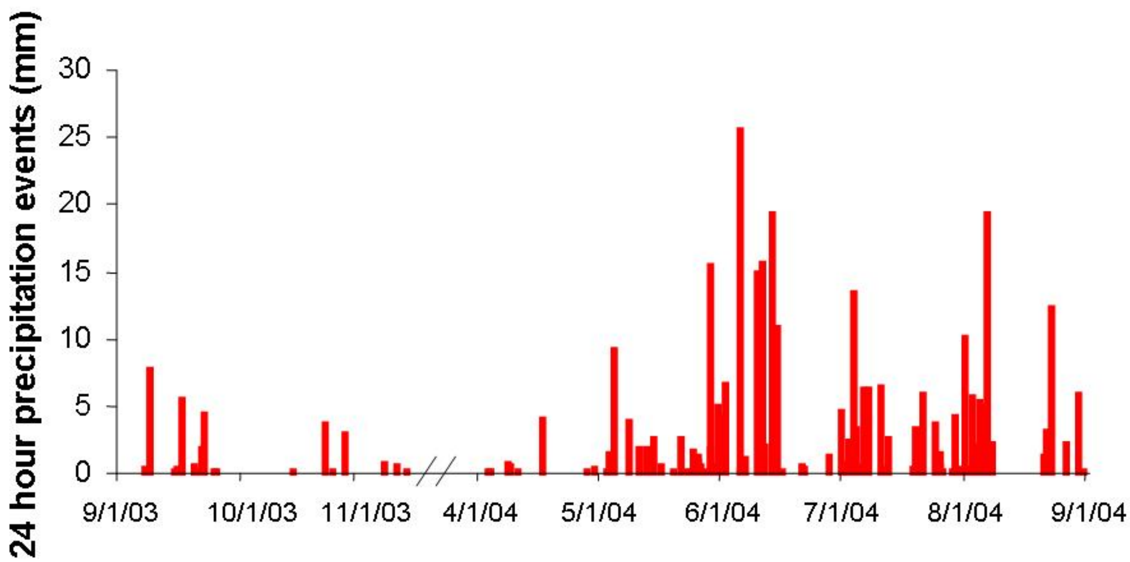

Figure 4.6. Total 24 h precipitation (mm/day) throughout monitoring period (including Kindersley supplemental data).

Three wet periods were also identified during the study period. A total of 90 mm of rain fell from June 6th to 16th, 2004, while 44 mm fell between July 1st and July 12th, 2004. Finally, the period from July 26th to Aug 8th, 2004 experienced a total of 56 mm of precipitation.

At the River Ridge feedlot from September 2003 to August 2004, there were no 30 min rain events greater than 5 mm, 47 half hour events of between 1.0 and 5 mm (Figure 4.8), 108 events from 0.5 to 1.0 mm, and 285 half hour rain events of less than 0.5 mm.

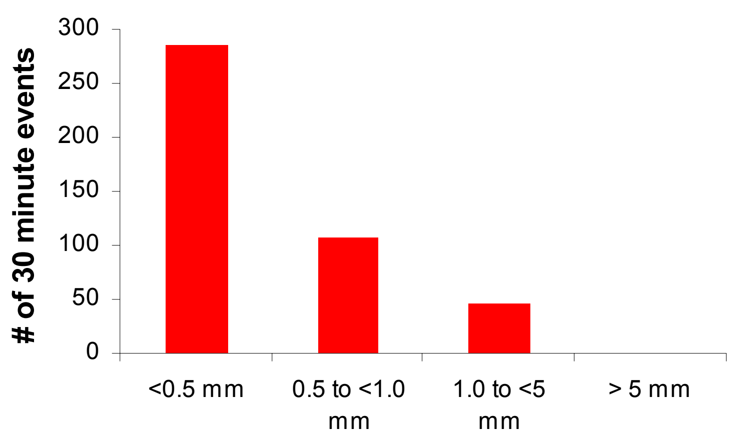

Figure 4.7. Number of 30 min rainfall events at feedlot during monitoring period (September 2003 to August 2004 as measured by feedlot meteorological station).

The two largest 30 min rainfall events recorded by the meteorological station at the River Ridge feedlot during the monitoring period were 4.5 mm received on June 14th, 2004 and 4.1 mm received on July 1st, 2004 (Figure 4.8).

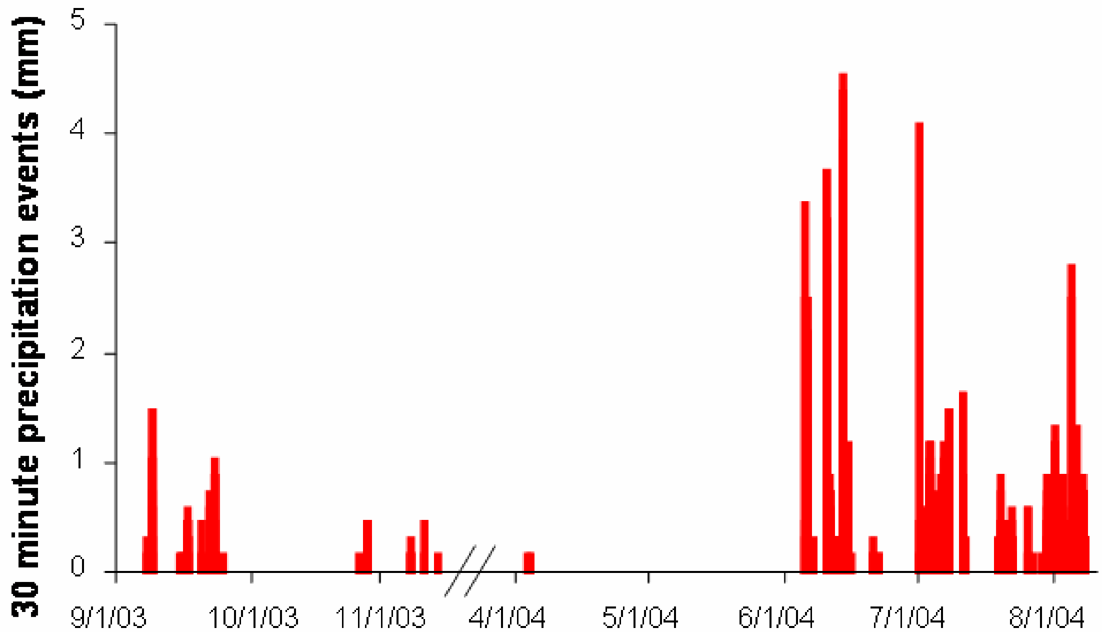

Figure 4.8. 30 min rainfall amounts during each rainfall event throughout monitoring period (as recorded by the feedlot meteorological station).

A runoff collection system was installed at the feedlot on July 1st of 2004, so the time period following installation is of interest in regards to rainfall intensity and duration. As can be observed from Figure 4.8, the largest 30 min rainfall event, after installation, at the feedlot was 2.8 mm on August 5th, 2004. The greatest 24 h rainfall event at the feedlot (during weir operation) was 19.3 mm received on August 7th, 2004 (Figure 4.6), which fell between the hours of 8 am and midnight. The largest 30 min rainfall event experienced on this day was 0.88 mm (Figure 4.8) at 11 am and 6 pm.

4.2.1.3 Rainfall Intensity-Duration Values for Saskatoon, Saskatchewan

Return periods of rain events were extracted from rainfall intensity-duration values for Saskatoon, Saskatchewan (Environment Canada 2004 for 1960-1992). Saskatoon was used as a basis for comparison because it had the most complete record for this region of the prairies. Table 4.9 and Figure 4.9 were derived to represent the rainfall duration intensity curves for five to 720 min duration storms. Thus, the frequency of storms of specific intensity and duration can be evaluated and were used to provide information for runoff prediction.

Table 4.9. Fitting coefficients for calculation of rainfall amount (mm) for durations between 5 and 720 min for return period of varying years.

a	b	time (min)
3.91	2.36	5
5.52	4.02	10
7.74	4.54	15
9.64	6.12	30
12.63	6.51	60
13.60	8.61	120
12.11	13.69	360
14.29	14.29	720

y = a ln(x)+b, where y is amount (mm) and x is return period in years

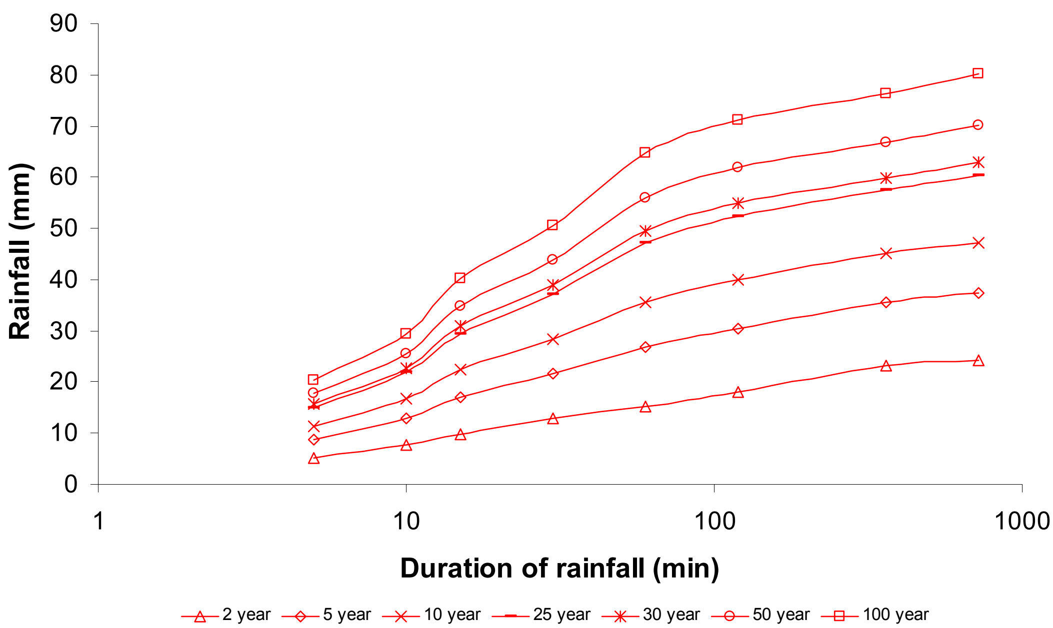

Figure 4.9. Rainfall duration curves for Saskatoon, Saskatchewan (Environment Canada 2004, 1960-1992).

From Figure 4.9 and Table 4.9, it is expected that a maximum 30 min amount of 12.8 mm would occur in a two year period and 6.1 mm in a one year period. This indicates that the 30 min rainfall events experienced at the River Ridge feedlot (Figure 4.8) are slightly less than what is expected for Saskatoon.

4.2.2 Cattle Moisture Inputs

Cattle moisture inputs, during the study year, were zero, due to the fact that the feedlot pens had no cattle in them during the monitoring period.

4.2.3 Potential Evaporation (PET)

Temperature is one of the main determinants of potential evaporation, and therefore, was examined at the River Ridge feedlot. The average annual temperature at Kindersley for 1971 to 2000 (Environment Canada 2004) was 2.9°C, while climatic normals for Eston for 1971 to 2000 (Environment Canada 2004) were slightly warmer than that of the long-term Kindersley data, with an annual temperature of 3.1°C (Table 4.10). The average annual temperature for Kindersley during 2003-04 (Environment Canada 2004) was the same as that of Kindersley long-term values, 2.9°C.

As stated earlier, the meteorological data for the feedlot during the warm season of the monitoring period was incomplete, so supplemental data from Kindersley was used to allow a more accurate estimation of the potential evapotranspiration at the River Ridge feedlot. Since the feedlot is slightly warmer and drier than Kindersley, the data used from Kindersley was corrected based on the calculated temperature difference between feedlot and Kindersley data for the warm season of 2003-04 (Appendix A). Thus, the potential evapotranspiration for the monitoring period was estimated to be 748 mm (Table 4.8).

4.2.4 Changes in Soil and Manure Moisture Storage (ΔS and ΔMP)

4.2.4.1 Change in Manure Pack Moisture Storage

The change in moisture storage of the manure pack at the River Ridge feedlot over the monitoring year was determined by first calculating the rough area of the feedlot pen covered by each type of manure pack. Approximately 60% of the pen was covered by a dry manure pack (including a 63 mm thick granular manure layer and a 50 mm thick compacted manure layer). As indicated in Table 4.10, 15% of the pen was covered by a compacted manure layer alone (since the granular layer had blown away on this part), and finally, 25% of the pen was covered by the remainder of the wet manure pack (between 250 to 500 mm depth, with an assumed thickness of 400 mm).

Table 4.10. Assumed change in moisture content of the inactive manure pack at the River Ridge feedlot over the monitoring period (Sept. 1, 2003 to Aug. 31, 2004)

Layer type	Coverage in feedlot pen (%)	Δmc in fall (mm)	Δmc in winter (mm)	Δmc in spring/summer (mm)
Granular layer and compacted layer	60	0	33 (20)	0
Compacted layer only	15	0	33 (5)	0
Wet manure pack	25	0	33 (8)	36 (9)
Total	100	0	33	9

Δmc: Change in moisture content (mm), Numbers in brackets are the change in moisture content based on the proportional coverage of the feedlot floor by the layer.

The change in moisture storage of the dry manure pack (including the granular and compacted manure layer) was estimated to be negligible for the fall months (Sept. and Oct., 2003, Table 4.10). This was based on the fact that only 28 mm of rainfall was received over the two month period, while potential evapotranspiration was calculated to be 149 mm. This small amount of precipitation would likely evaporate, rather than increase the moisture content of the manure pack beyond that of initial conditions (0.01 m^3/m^3 for the granular manure layer and 0.25 m^3/m^3 for the compacted manure layer, Table 4.5).

The snowpack at the feedlot was very thin (depth was not measured) and a site visit during spring melt revealed no observable runoff from the pens into the storage ponds. Analysis of Kindersley data (Table 4.7) for the monitoring period showed a snowfall water equivalent of 33 mm. The granular manure layer (63 mm in depth) at the River Ridge feedlot had an initial moisture content of 0.01 m^3/m^3 and a saturated moisture content of 0.82 m^3/m^3 (Table 4.5). Due to the dryness of the manure pack and the relatively small amount of snowmelt, all of the snow melt could have infiltrated into the manure pack and runoff would be negligible. Thus, the increase in moisture content of the dry manure pack over the winter months was estimated to be 33 mm (Table 4.10), assuming no wind blocking effects or midwinter sublimation.

The infiltration of 33 mm of snowmelt into the granular manure layer (63 mm depth) translates to an increase in moisture content of 0.52 m^3/m^3. Since the initial volumetric moisture content of the layer was 0.01 m^3/m^3 and the saturated volumetric moisture content was 0.82 m^3/m^3, this estimate is reasonable. It was assumed that this moisture evaporated with time throughout the following spring months.

Using the equation for infiltration of snowmelt into prairie agricultural soils (Equation 2.7), the amount of infiltration into the manure pack from snowmelt was calculated to be 33 mm.

The measured change in moisture content of the dry manure pack over the spring and summer months (Apr. through Aug., 2004) was negligible. Visual observation in August of 2004 confirmed that the dry manure pack still had a dusty, crumbly appearance, similar to that sampled in September of 2003.

The potential evapotranspiration for the spring and summer months was calculated to be 599 mm, while only 252 mm of precipitation was received during the same time period. A water balance calculation was performed between precipitation and potential evapotranspiration on a daily basis for July and August of 2004 (Appendix B) to determine if there was additional moisture present in the manure pack beyond that from precipitation by the end of the monitoring period. The balance indicated that there was not. It was assumed that for those days that daily calculations were performed, actual evaporation was equal to that of potential evapotranspiration, which is reasonable for a semi-arid climate. It was also assumed that the moisture stays within the manure pack and does not drain into the underlying soil below. For the portion of the feedlot pen that had only a compacted manure layer present, the same principles were assumed.

The top 200 mm of the wet manure pack had an initial moisture content of 0.49 m^3/m^3 (as sampled in Sept. 2003, Table 4.5). From July to Sept. of 2004, the moisture content of the wet manure pack for the 0-200 mm depth varied from 0.59 to 0.67 m^3/m^3 (Figure 4.10).

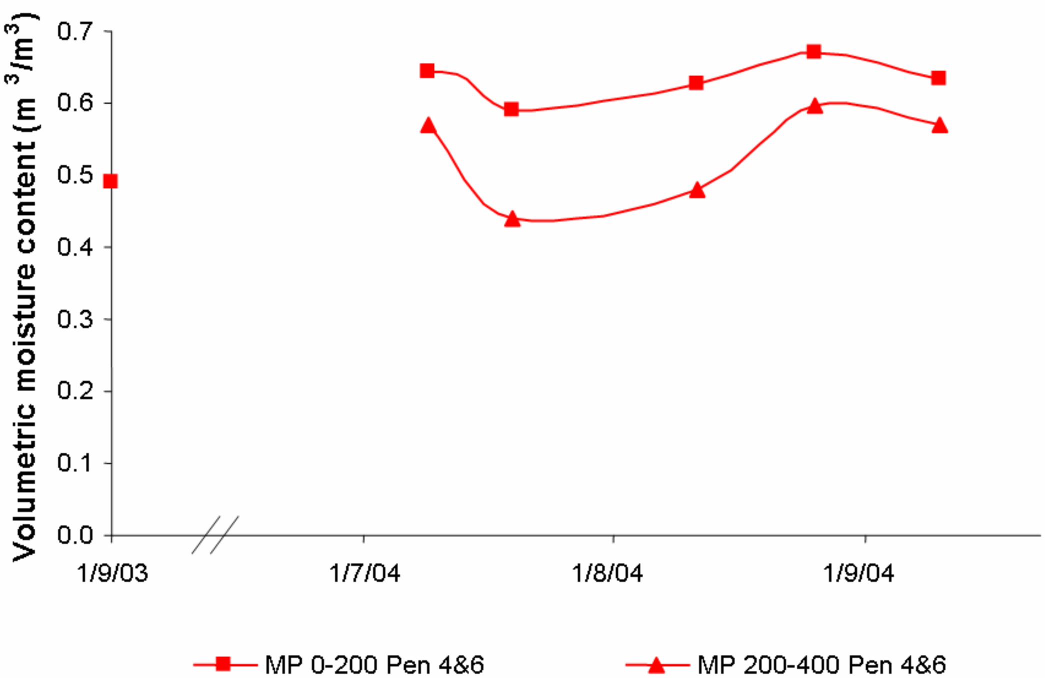

Figure 4.10. Volumetric moisture content of manure pack in feedlot pens from Sept. 2003 to Sept. 2004 to 400 mm depth. MP: wet manure pack samples.

The wet manure pack from 0-200 mm depth experienced an increase in moisture content of 0.18 m^3/m^3 for the monitoring year. This translated to an increase of 36 mm of water (Table 4.10). From July to Sept. of 2004, the moisture content of the wet manure pack for the 200-400 mm depth remained unchanged at 0.57 m^3/m^3 (Figure 4.10).

It is important to note that the large variability in the volumetric moisture contents at the 200-400 mm depth could be due to the presence of straw in the manure pack upon sampling. Also, volumetric moisture contents were calculated for each depth increment using bulk densities established from undisturbed cores (sampled in Aug. 2003), along with the gravimetric moisture contents of the disturbed samples. It was assumed that the disturbed soil samples taken at each sampling date had the same bulk density as the undisturbed samples taken in Aug. 2003.

4.2.4.2 Change in Soil Moisture Storage

Soil samples beneath the wet manure pack, as well as soil samples of the scraped soil surface (no manure pack cover present), were taken at several depth intervals over the monitoring year at the River Ridge feedlot. The September 2004 samples were taken outside the monitoring period ending in August 2004, but the samples were available to be used to supplement the data taken in July and August. In addition, disturbed soil samples were taken in 200 mm intervals to 0.6 m depth from three different sites in each pen on each visit with a 25 mm diameter hand auger. Volumetric moisture contents were calculated for each depth increment using bulk densities established from undisturbed cores (sampled in Sept. 2003), along with the gravimetric moisture contents of the disturbed samples. It was assumed that the disturbed soil samples taken at each sampling date had the same bulk density as the undisturbed samples taken in Sept. 2003.

The scraped soil surface of the feedlot pen showed greater change in soil moisture during the summer season than the soil covered with a manure pack in the soil depth intervals from 0-600 mm (Figure 4.11).

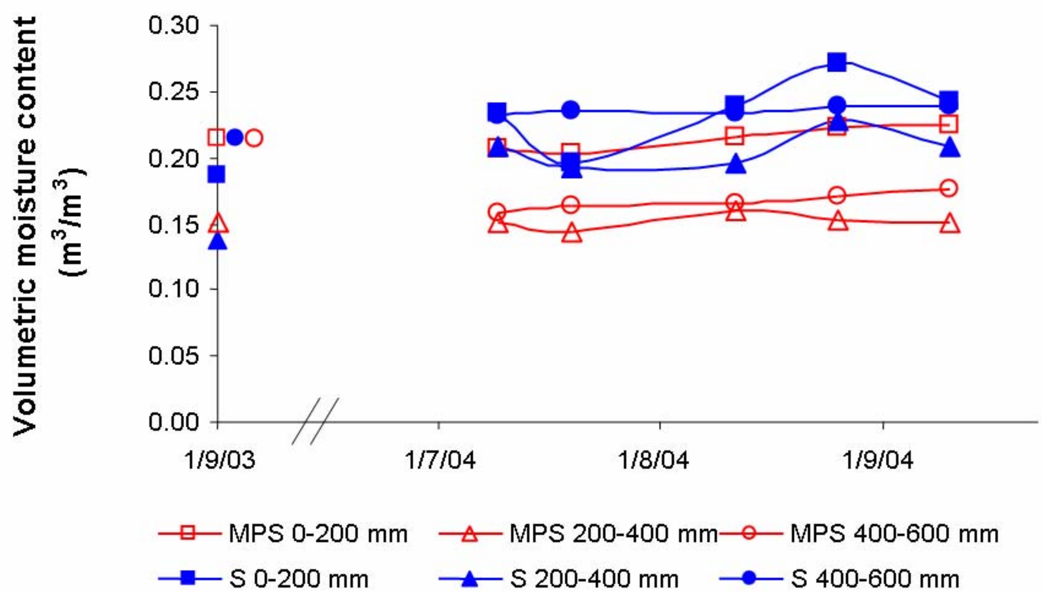

Figure 4.11. Volumetric moisture content of soil in feedlot from Sept. 2003 to Sept. 2004 to 0.6 m depth.
MPS: soil beneath the wet manure pack, S: scraped soil surface. Bulk densities determined earlier were used, along with the gravimetric moisture contents, as described in Section 3.3.4.

The top 200 mm of the scraped soil surface varied from a low of 0.19 m^3/m^3 on Sept. 15th, 2003 to a high of 0.27 m^3/m^3 on Aug 24th, 2004 (Figure 4.11), while the same soil interval under the manure pack changed very little (0.01 m^3/m^3 between the same dates). The lower depth intervals (200-400 and 400-600 mm) of the scraped soil surface were wetter than that of the soil under the manure pack and varied over the monitoring period from 0.14 to 0.23 m^3/m^3 (200-400 mm depth, Figure 4.11) and 0.21 to 0.24 m^3/m^3 (400-600 mm depth, Figure 4.11), while the same soil interval under the manure pack changed by 0.03 m^3/m^3 or less.

The overall change in soil moisture storage in the top 0.6 m of the scraped soil surface (Figure 4.11) over the monitoring period for the inactive feedlot translated to a 40 mm increase in water. This was based on a volumetric moisture content increase of 0.08 m^3/m^3 over the hydrological year within the top 200 mm of soil (16 mm), 0.09 m^3/m^3 for the 200-400 mm depth interval (18 mm), and 0.03 m^3/m^3 for the 400-600 mm depth interval (6 mm). For the summer months alone, the largest change in soil moisture storage was calculated to be 16 mm, based on an increase of 0.04 m^3/m^3 from July to September, 2004 within the top 200 mm of soil (8 mm), 0.03 m^3/m^3 for the 200-400 mm depth interval (6 mm), and 0.01 m^3/m^3 for the 400-600 mm depth interval (2 mm).

Based on the snowmelt infiltration equation (Equation 2.7), with a snowfall water equivalent of 33 mm (from Kindersley, Table 4.7), 13.7 mm could have infiltrated into the scraped soil surface (Equation 2.7). This translated to an increase of 0.05 m^3/m^3 in the top 300 mm of soil (from Gray et al., 1985). Since the scraped soil surface at the feedlot had an initial moisture content of 0.21 m^3/m^3 (from September of 2003 for 0-50 mm soil depth, Table 4.5) and a saturated moisture content of between 0.32 and 0.47 m^3/m^3 (for 0-50 mm to 200-250 mm soil depth, Table 4.5), this snowmelt infiltration estimate was reasonable. It was assumed that this moisture evaporated with time throughout the following spring months.

A certain amount of variability is expected with soil moisture samples, so the change of 0.01 m^3/m^3 or less was considered zero within range of experimental error based on the accuracy of the measuring equipment. Thus, the change in soil moisture storage in the top 0.6 m of the soil beneath the manure pack (Figure 4.11) for the inactive feedlot was calculated to be negligible (from an increase of 0.01 m^3/m^3 within the top 200 mm of soil, no change for the 200-400 mm depth interval, and a 0.01 m^3/m^3 increase for the 400-600 mm depth interval).

This finding of a negligible moisture content change in the soil beneath the dry manure pack is supported by Kennedy et al. (1999), who reported that the soil-water content of soil beneath an active feedlot varied little with time, due mainly to the manure/soil interface layer that limited water movement into or out of the soil.

4.2.5 Drainage (D)

The values for volumetric moisture content for depths of 0.6 to 1.2 m were used to determine if drainage due to excess moisture occurred at the River Ridge feedlot. The volumetric moisture content of the soil beneath the manure pack from 0.4 to 0.6 m depth ranged from 0.16 and 0.18 m^3/m^3 (Figure 4.11). Since the field capacity was measured to be 0.24 m^3/m^3 (400-450 mm depth soil, Table 4.6), it can be assumed that no drainage due to moisture in excess of field capacity took place below a depth of 0.6 m.

For the 0.6 to 0.8 m depth increment, the volumetric moisture content with depth increased by 0.02 m^3/m^3 from Sept. 2003 to Aug. 2004 (Figure 4.12). Over the same time period, the 0.8 to 1.0 m depth experienced no change in volumetric moisture content, while the 1.0 to 1.2 m depth showed a 0.06 m^3/m^3 increase (Figure 4.12). The increase at this depth increment cannot be explained, but could be due to temperature related effects on the TDR probes, as there was little precipitation in May 2004, but the soil moisture content at the 1.0 to 1.2 m depth increment during this time period increased.

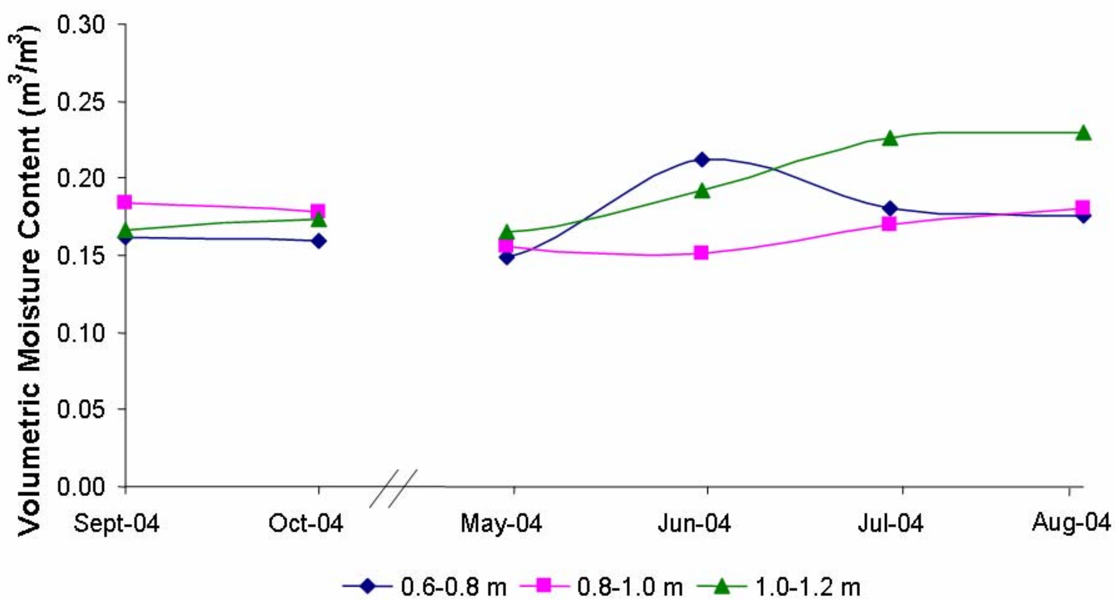

Figure 4.12. Volumetric moisture content from 0.6 to 1.2 m depth in feedlot pens. Average of 2 values for each month from Sept. 2003 to Aug. 2004 for each depth increment. The soil was frozen from November 2003 to April 2004, thus readings were not reliable and were not used.

Various authors such as Joshi and Maule (2000) and Dyck et al. (2003) have quantified drainage below a depth of 1.0 m in the prairies, with values ranging from 2 to 11 mm/year. Maule and Fonstad (2002) calculated a value of 2 to 6 mm for active feedlots in Saskatchewan. This value for drainage could be comparable to that of the River Ridge site conditions, considering that both the Maule and Fonstad (2002) study site and the River Ridge feedlot were located in Saskatchewan, characterized by coarse textured glaciolacustrine material.

On the other hand, the study by Maule and Fonstad (2002) was carried out on an active feedlot. Thus, the manure pack would have a relatively high moisture content in comparison with the inactive, dry manure pack at the River Ridge feedlot. In addition, the River Ridge feedlot received less precipitation (371 mm for Maule and Fonstad, 282 mm for River Ridge feedlot). These factors indicate that the feedlots investigated by Maule and Fonstad (2002) would have higher drainage rates than experienced at the River Ridge feedlot, which supports the determination of minimal drainage due to excess soil moisture at the River Ridge feedlot.

4.2.6 Infiltration (I)

Infiltration measurements were used to help predict and interpret runoff components of the water balance at the River Ridge feedlot. Several methods were used at the feedlot to measure infiltration through the feedlot floor. Field methods included a Guelph rainfall simulator II and double ring infiltrometer, while the falling head method was used on cores within the laboratory. As can be seen in Table 4.11, the saturated hydraulic conductivities determined by these methods exhibited a large difference.

Table 4.11. Steady-state infiltration rates (double ring infiltrometer, rainfall simulator, and laboratory saturated hydraulic conductivities).

	Infiltrometer (cm/s)	Simulator (cm/s)	Laboratory K_s (cm/s)
Field soil	1.4×10^{-3} (1.3×10^{-3})	$>1 \times 10^{-3}$	NA
Dry manure pack	5.5×10^{-3} (3.5×10^{-3})	8.1×10^{-4} (6.8×10^{-5})	*6.3×10^{-6} (2.7×10^{-5})
Scraped soil surface	NA	4.7×10^{-4} (1.4×10^{-4})	5.1×10^{-6} (8.5×10^{-5})

Number of samples: field double ring (3); pen manure double ring (3); rain pen manure (2); rain pen soil (2); Dry manure pack lab Ks (7); Scraped soil surface lab Ks (10). NA: data not available, *Ks is only for the compacted manure layer of the dry manure pack. All values given are average values, numbers in brackets are standard deviations.

Field measurements are more representative of true conditions than lab measurements, however the field measurements of saturated hydraulic conductivity taken at the River Ridge feedlot had numerous errors, which are detailed below. Lab measurements are likely accurate for the samples measured, but not truly representative of field values. As a result, the laboratory values measured with the falling head permeameter method were used for further calculations.

Comparison of the laboratory saturated hydraulic conductivity values to the steady-state infiltration rates of the rainfall simulator and ring infiltrometer showed much lower rates for both the manure pack and for the scraped soil surface (about two orders of magnitude) (Table 4.11). Numerous difficulties were encountered with the feedlot floor conditions during the double ring infiltrometer tests and contributed to a number of possible sources of error. The soil and compacted manure layer was very hard and were difficult to sink the steel rings of the double ring infiltrometer into it. This lack of proper installation thus resulted in possible lateral seepage from beneath the steel barriers. Therefore, the saturated hydraulic conductivities calculated for the double ring infiltrometer tests are likely much higher than true pen conditions and were not used for further calculations.

With a single ring infiltrometer, Kennedy et al. (1999) found an initial saturated hydraulic conductivity rate of 9.3×10^{-5} to 4.5×10^{-4} cm/s for an active feedlot with an intact wet manure pack, and a rate approaching 0 cm/s after 137 h. Miller et al. (2003) also measured the saturated hydraulic conductivity at six locations at a feedlot in Alberta using a double ring infiltrometer. The reported infiltration rates varied from a minimum of 6.6×10^{-7} cm/s for the scraped soil surface of an active pen (with intact manure/soil interface) to 1.1×10^{-6} cm/s for a scraped pen surface with the manure/soil interface removed.

The saturated hydraulic conductivities measured by Kennedy et al. (1999) and Miller et al. (2003) were several orders of magnitude lower than that measured by the River Ridge feedlot samples for the double ring infiltrometer method (5.5×10^{-3} cm/s for the dry manure pack, Table 4.11). This may be due to the fact that the ring infiltrometer tests performed by these authors were conducted over a much longer period of time than those at the River Ridge feedlot (80 to 210 min) and used bentonite to seal the base of the infiltrometer to prevent lateral seepage. In addition, the ring infiltrometer measurements at the River Ridge feedlot were only conducted on the dry manure pack and not the scraped soil surface, due to the hardness of the soil surface.

Steady-state infiltration rates of 4.7 x 10^{-4} and 8.1 x 10^{-3} cm/s were found at the River Ridge feedlot for the scraped soil surface and dry manure pack respectively, using a Guelph rainfall simulator II. Numerous difficulties were also encountered with the feedlot pens during the rainfall simulation tests contributing to a number of possible sources of error. During the rainfall simulations, it is likely that lateral seepage resulted from beneath the steel barriers due to the inability to accomplish a proper seal due to the hardness of the soil. In addition, the manure pack was very dry, hard, and very absorptive. When the steel siding was pushed into it, cracks could have developed aiding water entry deeper into the pack or to the soil.

A water balance for the rainfall simulation trials failed to account for the volume of water being rained on the test plot. Three to 8 h of rain at 34 to 39 mm/h intensity was added to the 1m^2 plot. Thus, 0.10 to 0.27 m^3 of water was added to the dry manure pack of 0.11 m^3 volume, confirming the presence of lateral seepage beneath the steel barriers.

Soil excavation after rainfall simulation tests on both the plots with a dry manure pack, as well as the scraped soil surface did not show any visible signs of seepage and comparisons of initial moisture content to post rainfall soil moisture content failed to account for the infiltrated moisture. Therefore, the laboratory measured saturated hydraulic conductivity values of 6.3 x 10^{-6} cm/s (for the dry manure pack) and 5.1 x 10^{-6} cm/s (for 0-50 mm depth of the scraped soil surface, Table 4.3) were used to model runoff from the manure pack, although it is important to mention that field measurements would likely not take into account the possible sealing of natural cracks in the samples from expansion of the clay in the soil during saturation of laboratory samples. This sealing process would have taken place when saturating the samples in the core sleeves for 24 h prior to the falling head permeameter tests, making saturated hydraulic conductivity values determined with this method possibly lower than the true values.

4.2.7 Runoff

4.2.7.1 Observed Runoff Events (R) from Weir Monitoring System

In order to measure actual runoff from the pens due to rainfall events experienced at the River Ridge feedlot, a V-notch weir system was installed. No runoff events were recorded during the operational period of July 1st to August 31st, 2004. One value (less than 0.1 mm) was recorded, but this was attributed to condensation, rainfall on the culvert system, rainfall on the scraped apron at the start of the culvert system, and temperature effects upon the pressure sensor.

While the weir was in operation, the maximum rainfall intensity experienced at the feedlot was 5.5 mm/h (from a 30 min event of 2.8 mm on Aug. 5th, 2004, Figure 4.8). There were five (24 h) rainfall events of greater than 10 mm/day, of which the largest was 19.3 mm received on August 7th, 2004 (Figure 4.3), which fell through the hours of 8 am and midnight. The largest 30 min rainfall event experienced on this day was 0.88 mm (Figure 4.8) at 11 am and 6 pm. None of these precipitation events produced any measurable runoff. It is also important to note that during the entire monitoring period (Sept. 2003 to Aug. 2004), there were no observed runoff events during site visits, nor any evidence of runoff events (from pooled water or that of fresh erosion rills in the sides of the storage pond).

The rainfall intensity and corresponding lack of runoff at the River Ridge feedlot coincides well with data from Miller et al. (2003), as they also measured relatively few runoff events from a feedlot floor in southern Alberta. Six runoff events occurred in 1998, three in 1999, one in 2000, none in 2001, and one in 2002. Rainfall depth ranged from 4 to 140 mm and the maximum rainfall intensity was between 1.2 to 15.2 mm/h. Since the rainfall intensities at the River Ridge feedlot (maximum intensity of 5.5 mm/h and a maximum 24 h event of 19.3 mm) were on the low end of that measured by Miller et al. (2003), it stands to reason that fewer runoff events would occur.

Miller et al. (2003) also found that minimum precipitation events of 4 mm would produce 0.6 mm and 0.2 mm of runoff (15.3 and 6.1% yield), and Kennedy et al. (1999) found a minimum rainfall depth of 54.4 mm (for storms with a return period of more than ten years) was required to produce a runoff depth of 11.8 mm, which results in a yield of 16.6%. In addition, a minimum precipitation event of between 7.4 and 22.1 mm (less than a two year return period) produced runoff from pens of 7.1 mm and 6.9 mm. It should be noted, that these rainfall events were experienced during an extremely wet period of May through September, 1994, and would likely have high initial moisture conditions.

This data does not correspond well with conditions experienced at the River Ridge feedlot, as the largest rainfall event of 19.3 mm (while the weir was in operation) produced no runoff at all. This lack of runoff may be due to the fact that the River Ridge feedlot was inactive at the time runoff was being monitored and the manure pack was very dry. In support of this finding at the River Ridge feedlot, Kennedy et al. (1999) reported that of the 13 runoff events recorded in 1994, five of the storm events had return periods greater than 50 years and the total precipitation for May through September was 251 mm. For Miller et al. (2003), a rainfall of 4 mm that produced runoff at the feedlot had a 5-day rainfall index of 36.2, which indicates very wet conditions.

For the River Ridge feedlot, the dry manure pack was very dry (0.01 m^3/m^3 for the granular manure layer and 0.25 m^3/m^3 for the compacted manure layer, Table 4.5), and therefore, would have taken a long time before producing any measurable runoff. As a result, any precipitation received at the River Ridge feedlot would have to first increase the moisture content of the dry manure pack before runoff could occur. The Kennedy et al. (1999) and Miller et al. (2003) studies listed above were conducted on active feedlots whose manure packs would have a much higher moisture content.

This lack of observed runoff at the River Ridge feedlot is supported by Kennedy et al. (1999), who stated that it is the initial moisture content of the wet manure pack that determines when, and if, runoff occurs from the feedlot floor. It is only when the manure pack is saturated that it will transfer all of the subsequent rainfall to runoff.

4.2.7.2 Observed Snowmelt Runoff Events (R)

The snowmelt infiltration equation (Equation 2.9) depends upon the initial moisture of the soil. As stated in Section 4.2.4.1, runoff from the snowpack at the River Ridge feedlot was observed to be negligible due to the dry feedlot surface conditions measured in Sept. of 2003 (initial soil and manure pack moisture content measurements, Table 4.5). These initial moisture content measurements are indicative of site conditions leading up to November (or freeze-up), as there was only 28 mm of rainfall received in September and October (Table 4.8), while potential evapotranspiration totalled 146.6 mm (Table 4.11). Thus, the dry soil conditions of

September and October (leading to freezeup) at the River Ridge feedlot were likely typical of the soil conditions as winter approached.

Based on the snowmelt infiltration equation (Equation 2.7), with a snowfall water equivalent of 33 mm (from Kindersley, Table 4.7), 13.7 mm could have infiltrated into the soil (Equation 2.9) and contributed 19.3 mm of runoff for a scraped soil surface. For a dry manure pack surface, none of the snowmelt moisture would have become runoff.

Miller et al. (2003) discovered that of all 11 runoff events from a feedlot pen in Alberta, not one was generated by snowmelt. This corresponds well with the lack of runoff observed at the River Ridge feedlot. In their study, Kennedy et al. (1999) noted that all snow and manure was removed from the pens before snowmelt runoff could occur.

4.2.7.3 Runoff - Guelph Rainfall Simulator (GRS II)

The amount of time between start of rainfall and runoff initiation, as measured by the Guelph Rainfall Simulator (Table 4.12), indicated that pens with a manure pack took a long time for runoff to occur (generally greater than 2 h) as compared to pens with a scraped soil surface (less than 10 min).

Table 4.12. Infiltration and runoff data from rainfall simulation tests.

Conditions	t_s	i (mm/h)	r (mm/h)	f (cm/s)
Pen Soil	1 min	36	40	NA
Pen Soil	5 min 33 sec	57	38	5.3×10^{-4}
Pen Soil	2 min 50 sec	65	46	5.3×10^{-4}
Pen Soil	5 min 38 sec	68	45	6.4×10^{-4}
Pen Soil	4 min 15 sec	51	21	8.3×10^{-4}
Average		55	38	4.7×10^{-4}
Pen Manure	>1hr 45 min	34	0	9.4×10^{-4}
Pen Manure	>2hr 35 min	34	0	9.4×10^{-4}
Pen Manure	2 hr 45 min	39	10	8.1×10^{-4}
Pen Manure	8 hr	34	3.0	8.6×10^{-4}
Average		36	7.0	8.1×10^{-4}
Field	>2 hr 30min	36	0	8.1×10^{-4}

Scraped soil: Pen surface was scraped to reveal the soil surface, Pen manure: dry manure pack including the granular manure layer and the compacted manure layer, ts: time to start of runoff, or the time it rained before any runoff was recorded, i: rainfall rate as produced by the rainfall simulator, r: steady-state runoff rate, f: net infiltration rate (by difference method). Times with a '>' in front of did not have any runoff during the test duration. The thickness of granular manure layer was an average of 63 mm, the thickness of the compacted manure layer was an average of 50 mm.

The granular layer of the dry manure pack (63 mm in thickness, on average) was determined by visual inspection to pool water on the manure surface during the rainfall simulation trials. This pooled water was likely present because of the low hydraulic conductivity of the compacted manure pack and underlying soil layer. With excavation of the dry manure pack into the underlying soil layer, the granular layer of the dry manure pack was found to be extremely wet, and when sampled, would settle out of suspension with the water from the rainfall simulation. Thus, the granular manure layer was determined to be saturated at the end of each rainfall simulation trial. Subsequent laboratory tests conducted on samples of the layer taken before rainfall simulations determined the saturated volumetric moisture content (Table 4.5).

Runoff was generated within several minutes on the scraped soil surface (Table 4.12). This scraped soil surface was a result of scraping and/or chipping away the manure pack to expose the soil surface underneath. From visual observation during the rainfall simulation trials, ponding of rainfall in small depressions on the soil surface occurred for several min before runoff began.

Steady-state runoff rates for the scraped soil surface were reached for all but one of the simulation trials (Figure 4.13) within ten min after runoff had started.

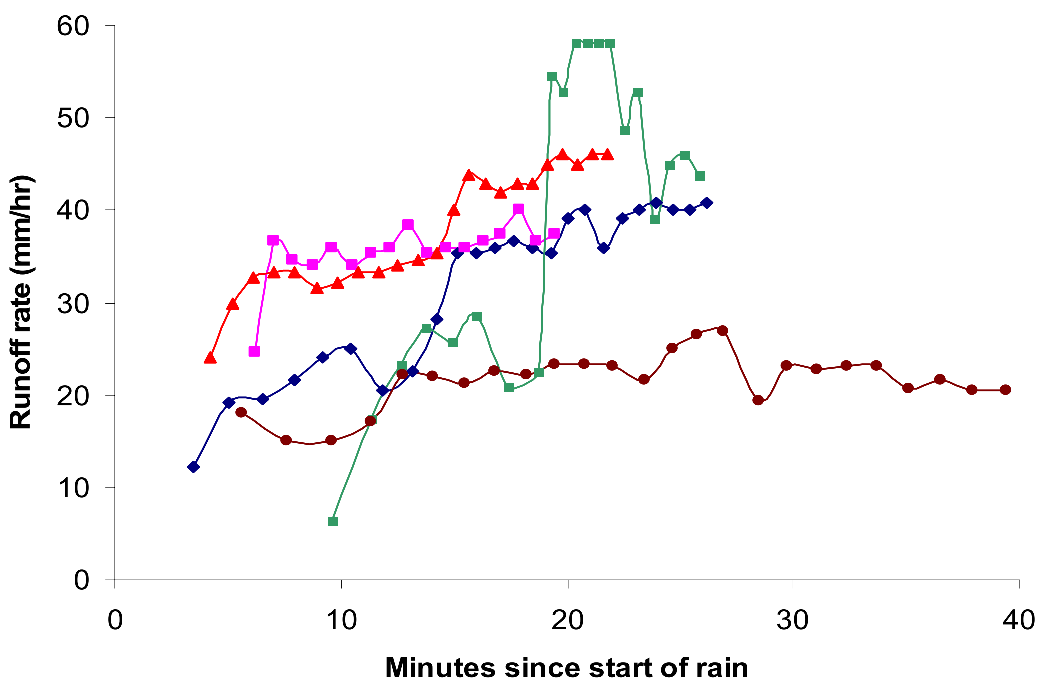

Figure 4.13. Measured runoff rates from a scraped soil surface from rainfall simulations in feedlot pens (lines with symbols for different trials).

One rainfall simulation trial (line with squares, Figure 4.13 rainfall rate of 68 mm/h) was highly variable throughout the trial period. The reason for this variable runoff rate might be due to the release of water from small depressions on the soil surface as the rainfall simulation progressed.

Miller et al. (2003) also conducted a study on active feedlot pens with the Guelph rainfall simulator II. They found that the time to start of runoff was mainly affected by depth of manure pack and moisture content. They also noted that instantaneous runoff measurements were often in excess of the rainfall rate due to water being released from hoof-print depressions by the cattle. For a rainfall rate of 54 mm/h, the time to start of runoff varied from 10.7 min for a pen floor to 21.6 min for a bedding pack. In addition, they also found a runoff rate of 48 mm/h for the bedding pack and 50 mm/h for the pen floor. These findings are very different from the time to runoff and runoff rate found at the River Ridge feedlot (conducted on the pen floor only), mainly due to the fact that the feedlot was inactive and had a dry manure pack. For rainfall rates between 34 and 39 mm/h the time to runoff on the dry manure pack ranged from 2 h and 45 min to 8 h, and runoff rates ranged from 3 to 10 mm/h (Table 4.12).

4.3 Missing Data and Modeled Hydrological Components

4.3.1 Runoff Estimation with the Green-Ampt Model

4.3.1.1 Using Rainfall Simulation Data on a Scraped Soil Surface

There has been no known research involving the validation of runoff from feedlots using the Green-Ampt runoff model. Yu (1994) analyzed rainfall-runoff data from bare plots in Australia with the Green-Ampt model and noted estimated Green-Ampt parameters using soil properties are usually inadequate and parameter values are better calibrated from measured runoff data. For runoff modeling at the River Ridge feedlot, initial Green-Ampt parameters were estimated using measured soil properties. Runoff rates from rainfall simulation trials were then used to calibrate the initial Green-Ampt parameters, so that runoff estimated by the model closely matched that measured in the field.

The saturated hydraulic conductivities used in the Green-Ampt model were based on rainfall simulation and laboratory measured values for the soil. Saturated hydraulic conductivity values for the soil of between 5.1 x 10^{-6} cm/s (from laboratory measurements for 0-50 mm depth, Table 4.3), Table 4.3), and 4.7 x 10^{-4} cm/s (from rainfall simulator measurements, Table 4.12) were used in the Green-Ampt model to estimate runoff from the scraped soil surface.

The moisture deficits used in the Green-Ampt model were based on the initial and saturated volumetric moisture contents of the feedlot pens. The average initial moisture content of the soil from 0-100 mm depth was measured to be 0.20 m^3/m^3 (Table 4.5) and the average saturated volumetric moisture content for the same depth was 0.35 m^3/m^3 (Table 4.5). Thus, a moisture deficit of 0.15 m^3/m^3 was used in the Green-Ampt model.

The rainfall rates used in the model were based on those of the rainfall simulation trials. Minimum and maximum rainfall rates of 36 to 68 mm/h were used for the rainfall simulations on the scraped soil surface, along with an average rainfall rate of 55 mm/h (Table 4.12). In addition, the greatest 30 min rainfall event measured at the feedlot while the weir was in operation, which totaled 5.5 mm/h (Figure 4.8), was also used in the model.

The wetting front suctions used in the model were based on saturated volumetric moisture contents of the soil. A wetting front suction of -300 mm was calculated from Equation 2.5 based on a saturated soil moisture content of 0.40 m^3/m^3 (from an average for all soil depths, Table 4.5).

A sensitivity analysis (Appendix C) was performed using the Green-Ampt model based on a range of values that were encountered in the field or laboratory (detailed above) in an attempt to adjust the model to the rainfall simulation data. Moisture deficits of 0.2, 0.15 and 0.1 m^3/m^3, saturated hydraulic conductivities of 5.1 x 10^{-6}, 8.5 x 10^{-5}, and 4.7 x 10^{-4} cm/s, rainfall rates of 36, 55 and 68 mm/h, and wetting front suctions of -300 mm, -150 mm, and -450 mm were used in the sensitivity analysis.

The parameters that had the greatest role in influencing the time before runoff begins on a scraped soil surface were rainfall rate and saturated hydraulic conductivity. Moisture deficit and tension at the wetting front played a minor role in influencing time to runoff.

The results of the Green-Ampt model plotted against six infiltration tests on a scraped soil surface using the rainfall simulator are shown in Figure 4.14. The saturated hydraulic conductivity that best matched the rainfall simulations for time to start of runoff and steady-state runoff rate was 8.5 x 10^{-5} cm/s, which was in between that of the rainfall simulator and the laboratory measured values. Other initial parameters remained the same as those for the rainfall simulations (Table 4.13).

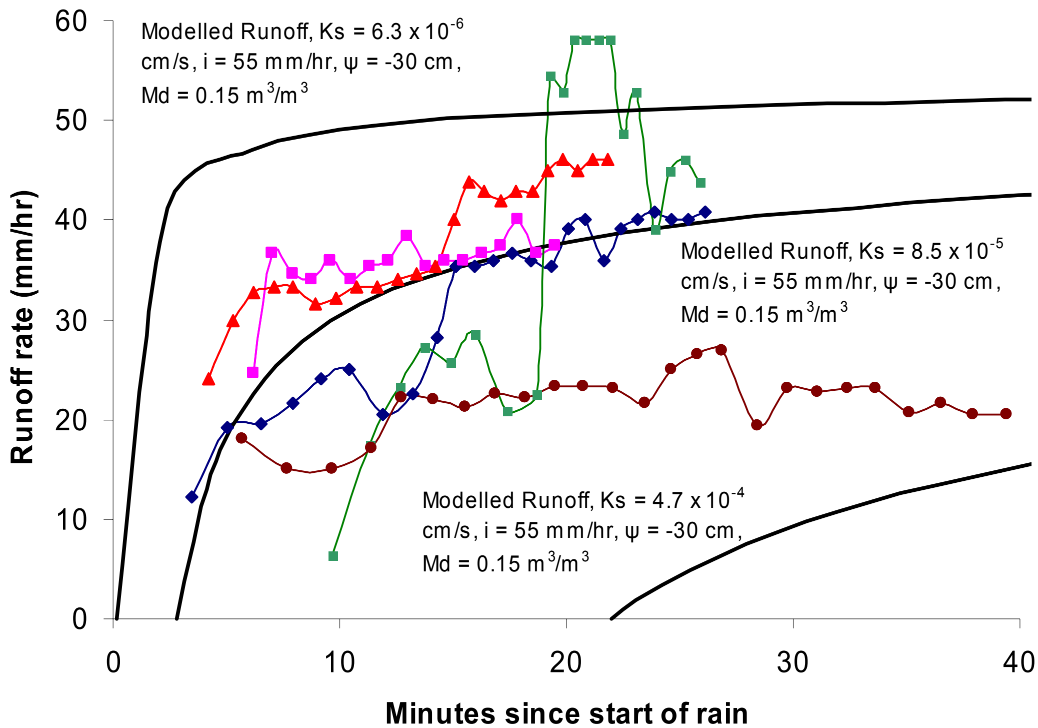

Figure 4.14. Measured (lines with symbols) and simulated (solid black lines) runoff rates from a scraped soil surface and various saturated hydraulic conductivities.

Table 4.13. Input parameters for Green-Ampt model for scraped pen soil.

	Units	Definition	Value	Source
K_s	cm/s	saturated hydraulic conductivity	8.5 x 10^{-5}	estimated
θ_s	m^3/m^3	saturated moisture content	0.35	calculated
θ_i	m^3/m^3	initial moisture content	0.2	field measured
M_d	m^3/m^3	moisture deficit	0.15	calculated
ψ	mm	wetting front suction	-300	Saxton et al. 1985
i	mm/h	rainfall rate	55	measured

When attempting to relate modeled runoff (with Green-Ampt) with measured runoff from the rainfall simulation on the scraped soil surface, the laboratory measured saturated hydraulic conductivity (5.1×10^{-6} cm/s) was too low in comparison with measured runoff. From the sensitivity analysis (Appendix C), a saturated hydraulic conductivity of 5.1×10^{-6} cm/s does not correlate well with any rainfall rate (36 to 68 mm/h), as runoff may start too soon (0.1 to 0.4 min after rain starts) compared to measured values from the rainfall simulation trials.

In addition, the saturated hydraulic conductivity measured by the rainfall simulator (4.7×10^{-4} cm/s, Table 4.12) was too high to correspond well with the measured runoff. For example, a saturated hydraulic conductivity of 4.7×10^{-4} cm/s with a rainfall rate of 35 to 68 mm/h, and moisture deficit of 0.15 m^3/m^3 does not correlate well with rainfall simulation trials, as runoff starts too late (Appendix C).

As discussed earlier, the rainfall simulator infiltration (saturated hydraulic conductivity) values may be higher than actual due to leakage during the field tests, and the laboratory values might be lower than actual values because they did not take into account the possible sealing of natural cracks in the samples (when saturating the samples for falling head permeameter tests). In the end, the best match to the rainfall simulator runoff measurements was a saturated hydraulic conductivity of 8.5×10^{-5} cm/s. According to the Green-Ampt model (and parameters listed in Table 4.13), a saturated hydraulic conductivity of 8.5×10^{-5} cm/s and a rainfall intensity of 55 mm/h should take approximately 2.8 min to create runoff, with a runoff rate of 42 mm/h after 40 min of rainfall (Figure 4.14). The time to runoff with the rainfall simulations on the scraped soil surface was less than this value, as 55 mm/h average rainfall intensity caused runoff to begin, on average, after 4.3 min (Table 4.12), with a steady-state runoff rate of 38 mm/h (approximately 40 min after the start of rainfall).

The relatively short time to start of runoff generated by the model (2.8 min) may be due to the fact the Green-Ampt model calculates it as the time at which water starts ponding on the ground. Thus, it may be another one to two minutes before this ponded water becomes runoff, which is when the rainfall simulation trials (4.3 min) began recording runoff. As a result, it appears that a saturated hydraulic conductivity of 8.5×10^{-5} cm/s correlates well for the average rainfall simulation trial rainfall rate of 55 mm/h and an average moisture deficit for both pens of 0.15 m^3/m^3.

It should be noted, though, that several other combinations of parameters correlate well with the measured runoff rate, as detailed in Figure 4.15.

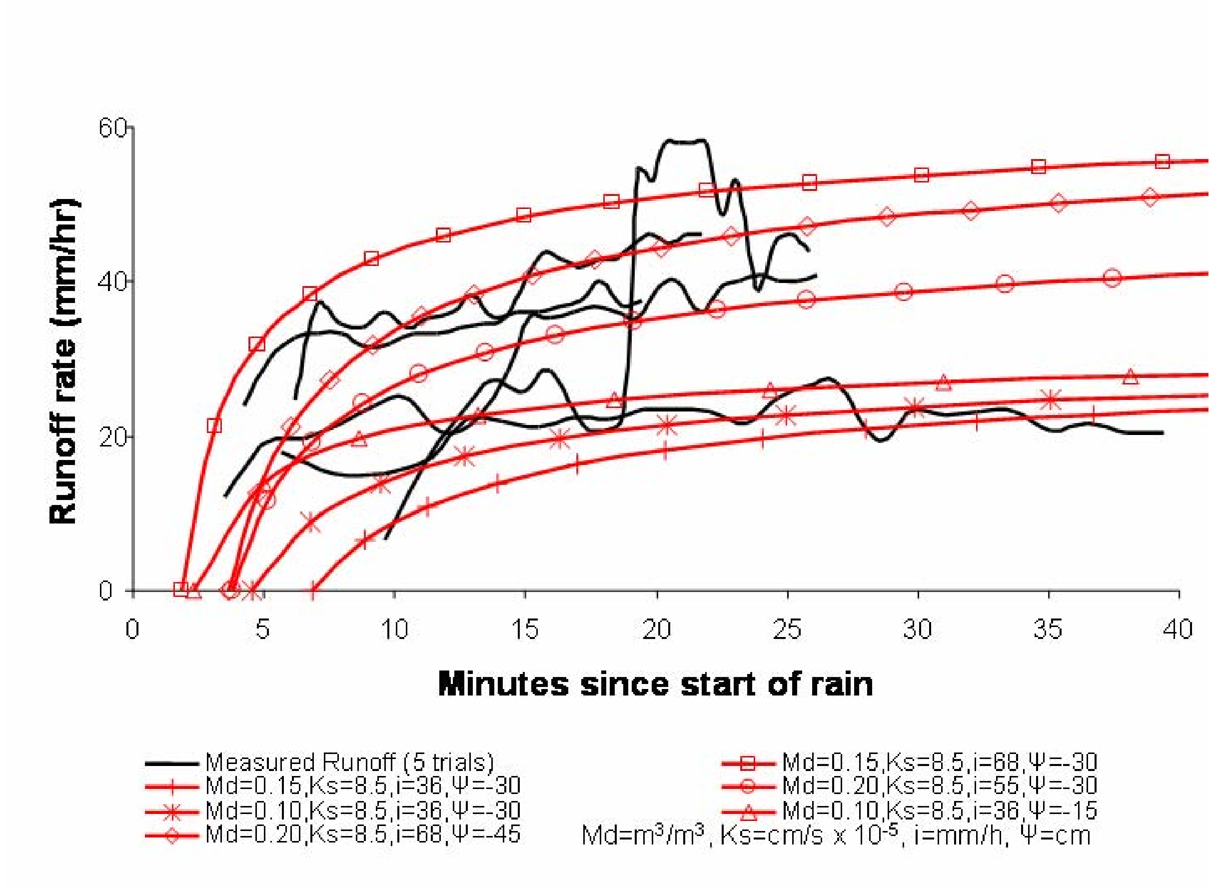

Figure 4.15. Measured (solid black lines) and simulated (lines with symbols) runoff rates from a scraped soil surface and various Green-Ampt model input parameters.

Figure 4.15 illustrates appropriate runoff start times in comparison to measured values from the rainfall simulation trials for several different combinations of parameters and the final runoff rates are still within limits measured during the rainfall simulation trials. Parameters such as wetting front suction were calculated from a fitting equation (Equation 2.5) and could be valid for a range of values. Several different rainfall rates are also valid for the model, as a range of rates were used for the rainfall simulation trials. Moisture deficits other than measured values (0.15 m^3/m^3) are possible, but unlikely, and saturated hydraulic conductivities other than 8.5 x 10^{-4} cm/s do not correlate well with measured runoff values.

4.3.1.2 Using Feedlot Rainfall Data on a Scraped Soil Surface

The Green-Ampt model was used to relate predicted runoff for a scraped soil surface with that measured at the feedlot with the rainfall simulations. This rainfall simulation data was appropriate to compare to the runoff prediction model because the rainfall simulations measured runoff from a scraped soil surface, while the weir collection system measured runoff from a variety of surfaces, including the dry manure pack.

The greatest 24 h precipitation events of 19.3 mm and 25.5 mm were received on August 7th and June 6th, 2004 (Figure 4.6). The largest 30 min rainfall event on Aug. 7th was 0.88 mm (Figure 4.8). Thus, using a rainfall intensity of 1.8 mm/h (from 0.88 mm/0.5 hr), no runoff would be produced, because the rainfall rate is less than the infiltration rate of the scraped soil surface (the best fit hydraulic conductivity of 8.5 x 10^{-5} cm/s, Table 4.13). On June 6th, the highest 30 min rainfall was 2.5 mm. This translates to a rainfall intensity of 5.0 mm/h, which would create runoff after 810 min (Appendix C). It must be mentioned, though, that the rainfall intensity of 5.0 mm/h only lasted for 30 min, and then the rainfall rate for the next 30 min dropped to below the saturated hydraulic conductivity of the soil surface, which indicates that there would be no runoff from this rainfall event.

From Figure 4.3, three wet periods occur during the study period; June 6th to 16th, 2004 (total of 90 mm), July 1st to July 12th (total of 44 mm), and July 26th to Aug 8th, 2004 (total of 56 mm). Even though the two greatest 24 h rainfall events fell within a wet period, if the individual 30 min rainfall intensities for each storm detailed above (24 h amounts of 25.5 mm and 19.3 mm) are used in the Green-Ampt model, neither of them would generate any runoff, regardless of the moisture deficit, as the 30 min rainfall intensities during each event are less than the saturated hydraulic conductivity of 8.5 x 10^{-5} cm/s.

If the greatest 30 min intensities (and their associated storms) are used in the Green-Ampt model for a scraped soil surface (4.5 mm from June 14th, 4.1 mm from July 1st, and 2.8 mm from Aug. 5th, Figure 4.8), runoff will still not result (Appendix D). Thus, regardless of the type of rainfall event experienced at the River Ridge feedlot (largest 24 h amounts, largest 30 min intensities, largest storm events, and precipitation received during wet periods), no runoff would be produced based on the Green-Ampt runoff model and parameters detailed above.

4.3.1.3 Using Rainfall Simulation Data on a Manure Pack

There has been no known research involving the validation of runoff from feedlot manure packs using the Green-Ampt runoff model. Therefore, the measured runoff from rainfall simulation trials, as well as physical and hydrological properties of the manure pack, were used to determine model parameters so that runoff estimated by the model could be calibrated to measured runoff.

Saturated hydraulic conductivity values from 6.3 x 10^{-6} cm/s (average for the compacted layer of the dry manure pack from lab measurements, Table 4.3) to 8.1 x 10^{-4} mm/h (for the dry manure pack from rainfall simulator measurements, Table 4.12) were also used in the runoff model for prediction of runoff from the feedlot floor.

The initial moisture content of the granular layer of the dry manure pack was measured to be 0.01 m^3/m^3 (Table 4.5) and increased to 0.82 m^3/m^3 upon saturation in the laboratory (Table 4.5). Thus, the moisture deficit for the granular layer of the manure pack was approximately 0.80 m^3/m^3. The initial moisture content of the compacted manure layer of the dry manure pack was measured to be 0.25 m^3/m^3 and increased to 0.44 m^3/m^3 (Table 4.5) upon saturation. Thus, the moisture deficit of the compacted layer of the dry manure pack was about 0.20 m^3/m^3.

An average rainfall rate of 36 mm/h (Table 4.12) was used for the rainfall simulations on the dry manure pack, which was approximately 113 mm thick (comprised of an average of 63 mm of granular manure layer and 50 mm of compacted manure layer). In addition, an average rainfall rate of 55 mm/h (Table 4.13) was used for the rainfall simulations on the scraped soil surface and the greatest 30 min rainfall event measured at the feedlot while the weir was in operation was 2.8 mm (Figure 4.5). This translates to a rainfall intensity of 5.5 mm/h.

A wetting front suction of -300 mm was chosen from a calculated air entry value (Equation 2.5) based on a saturated soil moisture content of 0.40 m^3/m^3 (from an average for all soil depths, Table 4.5). A wetting front suction of -150 mm was also used, based on a saturated soil moisture content of 0.35 m^3/m^3 (from an average for 0-100 mm depth, Table 4.5).

A sensitivity analysis (Table 4.14) with the Green-Ampt model was performed on the dry manure pack based on a range of values that were measured in the field or laboratory (as described above).

Table 4.14. Sensitivity analysis for time to start of runoff on manure pack.

Ψ (mm)	K_S (cm/s)	i (mm/h)	M_D (m^3/m^3)	t_S (min)
-300	6.3×10^{-6}	36	0.8	2.2
-300	**3.3×10^{-4}**	**36**	**0.8**	**200**
-300	8.1×10^{-4}	36	0.8	1657
-300	3.3×10^{-4}	36	0.6	150
-300	3.3×10^{-4}	36	0.25	63
-300	3.3×10^{-4}	36	0.2	50
-300	3.3×10^{-4}	55	0.8	72
-300	3.3×10^{-4}	20	0.8	1080
-300	3.3×10^{-4}	5.0	0.8	never
-450	3.3×10^{-4}	36	0.8	300
-150	3.3×10^{-4}	36	0.8	100

Symbols listed in Table 4.13.

Within the range of expected values, the parameters that played a significant role in influencing the time before runoff begins on the manure pack were saturated hydraulic conductivity and rainfall rate (Table 4.14). Moisture deficit and wetting front suction played a more minor role in influencing time to runoff.

The results of the Green-Ampt model plotted against the infiltration tests on the manure pack using the rainfall simulator are shown in Figure 4.16. It appears that a saturated hydraulic conductivity of 3.3×10^{-4} cm/s and rainfall intensity of 36 mm/h were the best fit in comparison with measured runoff data, along with initial parameters from Table 4.15. As seen, a rainfall intensity of 36 mm/h and a moisture deficit of 0.8 m^3/m^3 would take 200 min (almost 3 h) for runoff to begin (Figure 4.16), with a steady-state runoff rate approaching 11 mm/h.

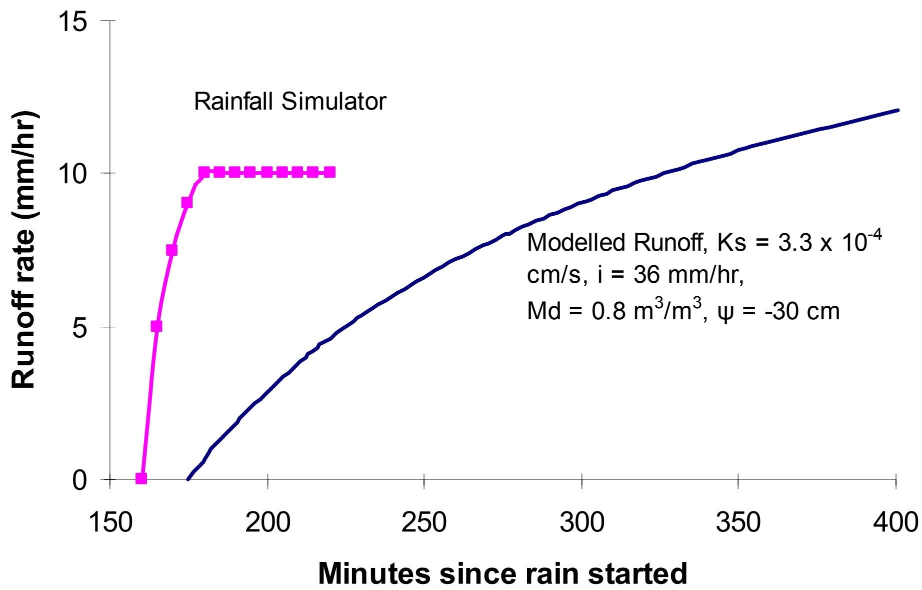

Figure 4.16. Estimated runoff rates from feedlot pens with a surface manure layer Green-Ampt parameters from Table 4.15, manure layer was assumed to have infinite depth.

Table 4.15. Input parameters for Green-Ampt model for manure pack in pens.

	Units	Definition	Value	Source
K_s	cm/s	saturated hydraulic conductivity	3.3×10^{-4}	lab measured
θ_s	m^3/m^3	saturated moisture content	0.81	lab measured
θi	m^3/m^3	initial moisture content	0.01	field measured
M_d	m^3/m^3	moisture deficit	0.8	calculated
ψ	mm	wetting front suction	-300	Saxton et al. 1985
i	mm/h	rainfall rate	36	measured

This time to start of runoff was comparable to that found in the field, as the granular layer of the dry manure pack rainfall simulator measurements required between 160 and 480 min to create runoff (if runoff started at all), with a steady-state runoff rate of 10 mm/h (for the one rainfall simulator trial that reached steady-state). The moisture deficit of 0.8 m^3/m^3 used in the model also corresponded well with the saturated volumetric moisture content of 0.82 m^3/m^3 measured in the lab for the granular layer of the dry manure pack (Table 4.5). Using an initial moisture content of 0.01 m^3/m^3 for the granular layer of the dry manure pack (Table 4.5), this would make the moisture deficit in the field 0.8 m^3/m^3, which was similar to that used in the Green-Ampt model. It is also interesting to note that the field measured (rainfall simulation) runoff achieved steady-state almost immediately after runoff started on the dry manure pack. This may be due to the relatively low hydraulic conductivity of the compacted manure layer or underlying soil.

The best fit saturated hydraulic conductivity of 3.3×10^{-4} cm/s falls between that measured by the rainfall simulator (8.1×10^{-4} cm/s, both the granular and the compacted manure layer, Table 4.12) and the laboratory measurements (6.3×10^{-6} cm/s, compacted manure layer, Table 4.3). The laboratory measured saturated hydraulic conductivity of the compacted manure layer was very low and when used in the model would create runoff after 2.0 min.

If the moisture deficit of the compacted manure layer (0.2 m^3/m^3, Table 4.5) is used in the Green-Ampt model (with a hydraulic conductivity of 3.3×10^{-4} cm/s), runoff would be produced after 50 min, which is too soon in comparison with the rainfall simulation values (Table 4.15).

It is important to note that the Green-Ampt model assumes homogeneous material of infinite thickness and thus is not able to model a two or three layer system as occurs at an inactive feedlot.

4.3.1.4 Using Feedlot Rainfall Data on a Manure Pack

If the highest 30 min and 24 h intensities (and their associated storms) detailed in Section 4.3.1.3 are used in the Green-Ampt model, runoff will not result, regardless of the moisture deficit, because each 30 min rainfall intensity experienced at the River Ridge feedlot was less than the infiltration rate of the manure pack (Table 4.11).

4.3.2 Estimated Runoff with the United States Department of Agriculture (USDA) Soil Conservation Service (SCS) Runoff Model

Various different curve numbers were found by other researchers (Table 2.3) depending on feedlot conditions. An average curve number of 68 was reported by Kennedy et al. (1999) for an active feedlot with a stocking density of 17 m^2/head, straw bedding, and relatively high initial moisture conditions. In addition, Miller et al. (2003) found a curve number of 80, on average, for a commercial unpaved feedlot with straw and wood-chip bedding, stocking density of 19 m^2/head, and wet initial conditions.

A reference curve number for a scraped feedlot soil surface could not be found, but was approximated as 90, based on the fact that a manure pack was not present and, therefore, would absorb little rainfall. Parker (1999a) reported curve numbers above 90 for a feedlot with extremely high precipitation conditions (440 to 960 mm per year) and Kizil and Lindley (2002) determined curve numbers of about 90 for a bison feedlot with a stocking density of 46 m^2/head. Both of these conditions were assumed to be similar to that of a scraped soil surface, as wet initial conditions (due to high precipitation and high stocking density) would cause little precipitation to be absorbed by the manure pack.

A reference curve number for a dry manure pack could not be found in the literature, but Burk et al. (2000) found that runoff curve numbers vary with initial soil water content. Therefore, a curve number of 60 was then chosen for the inactive River Ridge feedlot dry manure pack, considering that the average moisture conditions for the inactive manure pack are a great deal lower than that of an active feedlot (0.01 m^3/m^3 for granular layer of dry manure pack, 0.25 m^3/m^3 for compacted manure pack, and 0.46 m^3/m^3 for wet manure pack, Table 4.5).

Overall, then, for the River Ridge feedlot, a runoff curve number of 60 was chosen for the dry manure pack, 70 for the dry manure pack that had received a period of significant rainfall, 80 for a typical active feedlot wet manure pack, and 90 for a pen that has been scraped. Runoff curves were generated using the USDA SCS runoff method in order to relate predicted runoff with that measured at the feedlot with the weir.

Using the USDA SCS model (Equations 2.5 and 2.6) to predict runoff with a curve number of 90 for a scraped soil surface and the greatest 24 h precipitation event of 25.5 mm (Figure 4.6) that was experienced at the feedlot, approximately 8.2 mm of runoff would occur. Similarly, for a precipitation event of 19.3 mm (the largest received during the operation period of the weir), 4.5 mm would run off.

The minimum 24 h rainfall to produce runoff for an SCS Curve of 90 is 10 mm, which will produce 0.5 mm of runoff (Figure 4.17). Considering that there were ten events experienced at the feedlot of greater than 10 mm (Figure 4.5), there would be runoff produced for a scraped surface. Using an SCS curve number of 90 for each individual rainfall event (25.5, 19.4, 19.3, 15.6, 15.5, 14.9, 13.4, 12.4, 10.8 and 10.1 mm), a total of 28.9 mm would be predicted to run off from a scraped feedlot surface.

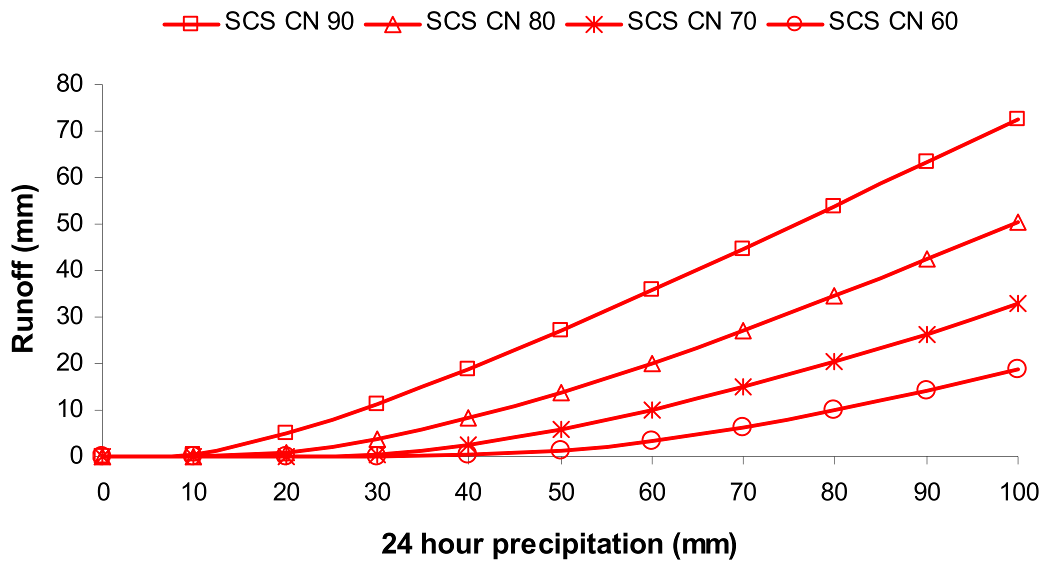

Figure 4.17. Runoff produced from 24 h rainfalls using SCS curve numbers of 60 to 90 in the USDA runoff model.

It is also interesting to note that storage values used in the USDA SCS model will also influence the volume of runoff from a feedlot. Miller et al. (2003) found storage values from 0.4 to 7.5 at an active feedlot, indicating a wide range in storage of water on the feedlot floor. They also noted that the USDA runoff model does not take the release of water from hoof-print depressions by the cattle into account. Thus, the USDA runoff prediction model would underestimate runoff if the release of this water was not considered.

Since there were no cattle in the pens when the rainfall simulations and other measurements were conducted, the dry manure pack surface was fairly smooth (Figure 3.10). Because this surface was smooth, there were very few hoof-print depressions to account for in the modeled runoff. Therefore, the storage parameter for runoff modeled at the feedlot was calculated based on the curve number chosen and was not manipulated in order to account for additional storage from hoof print depressions.

The USDA SCS model was used to relate predicted runoff with that measured at the feedlot. The minimum 24 h rainfall required to produce runoff for an SCS Curve of 60 is 40 mm, which produces 0.2 mm of runoff (Figure 4.17). Considering that there were no rainfall events of this magnitude experienced during the monitoring year (either when the weir was operational or not), no runoff would be produced.

4.3.3 Estimation of Runoff from the Wet Manure Pack

An estimation of runoff from the wet manure pack at the River Ridge feedlot was not made using either of the two runoff models. The wet manure pack, comprising 25% of the pen surface, had a relatively high saturated hydraulic conductivity (Table 4.3), was 250 to 500 mm thick, and was mixed with straw. As a result, it was assumed that the wet manure pack absorbed all of the rainfall it received and did not produce any runoff during the monitoring period.

The assumed lack of runoff corresponds well with Miller et al. (2003), who measured relatively few runoff events from the wet manure pack of a feedlot in southern Alberta. Only six runoff events were recorded in a five year period, and the hourly rainfall intensities and total 24 h rainfall amounts received at the Alberta site were greater than that experienced at the River Ridge feedlot.

4.3.4 Comparison of the Green-Ampt and USDA SCS Runoff Models

For the scraped soil surface, the amount of runoff calculated by the USDA SCS model (a total of 28.9 mm) is in contrast to the lack of runoff predicted by the Green-Ampt model for a scraped soil surface. For the dry manure pack, the two runoff models corresponded well in the prediction of no runoff from the dry manure pack for the precipitation events experienced during the monitoring year at the River Ridge feedlot. The USDA SCS model was used in the water balance of the River Ridge feedlot, as it is easier to use with the rainfall data measured at the feedlot and is the most commonly used model to predict runoff from feedlots (Kennedy et al. 1999, Parker et al. 1999a, Kizil and Lindley 2001, and Miller et al. 2003).

It must be noted, though, that the Green-Ampt runoff model can be more accurate than the USDA SCS model. The Green-Ampt model is physically based and can better explain the processes in the soil leading up to the start of runoff. In addition, the Green-Ampt model is based on on-site measured soil parameters, while the USDA SCS model is based on curve numbers that were found by other studies for active feedlots in other provinces and countries.

4.4 Summary and Water Balance Analysis

4.4.1 The Water Balance

A water balance was performed for two scenarios at the feedlot: that of an inactive pen with a scraped soil surface and an inactive pen with a manure pack over a hydrological year. It was carried out based on the adaptation of the following Gee and Hillel (1988) equation for a soil water balance:

$$P1 + P2 = AE + D + \Delta S + \Delta MP + R \tag{4.1}$$

where:

P1 = water added from precipitation (mm)

P2 = water added from cattle (mm)

AE = actual evaporation (mm)

D = drainage (mm)

ΔS = change in soil moisture storage (mm)

ΔMP = change in manure pack moisture storage (mm)

R = runoff (mm)

The water balance incorporated conditions that existed at the feedlot during the monitoring period (Sept. 2003 to Aug. 2004), such as lack of cattle and dry manure pack. Each of the parameters presented in the balance were calculated using values determined in the field and laboratory, as well as from runoff modeling (Table 4.16), and were reported in previous sections. Actual evaporation was determined by difference.

Table 4.16. Water balance of inactive feedlot pens with a scraped soil surface and a manure pack for Sept. 2003 to Aug. 2004.

	Scraped Pen Surface			Inactive Manure Pack		
	Fall 2003	Winter 2003-04	Spring and Summer 2004	Fall 2003	Winter 2003-04	Spring and Summer 2004
P1	28	33	252	28	33	252
P2	0	0	0	0	0	0
PET	149	0	599	149	0	599
D	0	0	0	0	0	0
ΔS	0	14	40	0	0	0
ΔMP	0	0	0	0	33	9
R	0	19	29	0	0	0
AE	28	0	183	28	0	243

P: precipitation, P2: moisture addition from cattle, PET: potential evapotranspiration, I: infiltration, D: drainage, ΔS: change in soil moisture storage in top 0.6 m of soil, ΔMP: change in moisture content of the manure pack, R: runoff, AE: actual evaporation, Spring/summer: April to Aug., Fall: Sept. and Oct., Winter: Nov. to Mar.

4.4.2 Manure Properties

During the monitoring period there were no cattle in the pens, however the remainder of the wet manure pack ranged from 250-500 mm in thickness, with the thickest areas located in the manure mound at the centre of the pen. The granular manure layer of the dry manure pack was loosely held together material of 2 and 3 mm to 50 mm diameter pieces, which formed after the cattle were removed from the pens. The granular layer, upon sampling, was very dry (0.01 m^3/m^3) and had a dry bulk density of 0.44 g/cm^3. Upon saturation in the lab, the volumetric moisture content increased to 0.82 m^3/m^3 and the bulk density decreased to 0.36 g/cm^3 due to swelling. Underneath the 63 mm thick granular manure layer was the 50 mm thick compacted manure layer of the dry manure pack, which was generally much harder, moister (0.25 m^3/m^3), and denser (0.78 g/m^3) than the granular manure layer above.

4.4.3 Soil Properties

The texture of the top 600 mm of the feedlot pens was loam (14 to 24% clay and 49 to 60% sand) and the top 50 mm of soil had an organic carbon content of 0.59%. The bulk density of the soil was highest in the top 100 mm (1.65 and 1.68 g/cm^3 at 0-50 mm and 50-100 mm depths, respectively) and was lowest (1.35 g/cm^3) at the 200-250 mm depth. The initial moisture content of the soil (as measured in Sept.

2003) was 0.21 m^3/m^3 for 0-50 mm depth and 0.19 m^3/m^3 for the 50-100 mm depth, which increased to 0.31 m^3/m^3 and 0.39 m^3/m^3, respectively, upon saturation.

Rainfall simulator tests on the bare pen soil at rainfall rates between 36 and 68 mm/h resulted in runoff occurring in 1 to 6 min. The simulator measured steady-state infiltration into the scraped soil surface of 4.7×10^{-4} cm/s, whereas the laboratory saturated hydraulic conductivity values were two orders of magnitude lower, at 5.1×10^{-6} cm/s. It was difficult to install the metal sides of the rainfall simulator boundary plates into the compacted manure layer and lateral flow could have accounted for the higher rates. In addition, the laboratory measurements for 0-100 mm soil depths were on undisturbed clods and the closure of naturally occurring cracks upon saturation could have also resulted in lower rates than would have occurred in the field.

4.4.4 Determination of Precipitation (P1)

During the study period (Sept. 1, 2003 to Aug. 31, 2004) the feedlot climate station was operational only 40% of the time. Equipment failures, combined with long distances from Saskatoon to the feedlot, resulted in an incomplete data set. To supplement the missing data, daily temperature and precipitation values were used from Kindersley (Environment Canada 2004), after correction.

Overall, the precipitation received at the River Ridge feedlot during the monitoring period in comparison with long term values is slightly more than average. Table 4.8 shows long-term Eston precipitation to be 234 mm during the months of April to October, while that measured at the River Ridge feedlot (including supplemental data from Kindersley) was 280 mm. Thus, the water balance performed with the feedlot rainfall data would likely represent a typical scenario for potential runoff during the warm season.

More specifically, the monitoring year started off very dry (fall precipitation received during September and October 2003 totaled 28 mm, Table 4.8) and continued so until June, when 96.9 mm of precipitation was received. Spring and summer precipitation totaled 252 mm (April through August, Table 4.8).

Winter season precipitation was that received at the feedlot during the months of November through March. Winter precipitation measurements from Kindersley for the monitoring period were used in the water balance instead of data from the feedlot site, as no snowfall measurements were taken at the feedlot.

Analysis of Kindersley data (Environment Canada 2004) for the monitoring period showed a snowfall water equivalent of 33 mm (Table 4.7).

During the entire monitoring period, there were 76 days with rainfall between 0.1 and 5 mm (Figure 4.5, including data supplemented from Kindersley) of which there were 10 events greater than 10 mm/day. From analysis of long-term Kindersley rainfall data (Figure 4.4), it can be expected that during a one year period 12.7 (24 h) events of less than 1 mm will occur and 5.5 events will occur of between 10 and 25 mm. Thus, the events experienced at the River Ridge feedlot were slightly above that of the expected values.

The largest daily rainfall amounts during the monitoring period were 25.5 mm received on June 6th, 19.4 mm received on June 14th, and 19.3 mm received on August 7th, 2004 (Figure 4.6). The two highest 30 min rainfall events during the monitoring period were 4.5 mm received on June 14th, 2004 and 4.1 mm received on July 1st, 2004 (Figure 4.8). From Figure 4.9, during a one year period, a maximum 30 min rainfall amount of 6.1 mm would be expected to occur, indicating that the 30 min events at the River Ridge feedlot were within norms for Saskatoon.

Finally, three wet periods occurred during the monitoring period; June 6th to 16th, 2004 (total of 90 mm), July 1st to July 12th (44 mm) and July 26th to Aug 8th, 2004 (total of 56 mm).

4.4.5 Determination of Moisture Input by Cattle (P2)

Moisture input for the inactive feedlot floor was zero, as there were no animals in the pens.

4.4.6 Determination of Potential Evapotranspiration (PET)

Including corrected supplemental data from Kindersley, the temperatures at the River Ridge feedlot during the monitoring period were slightly different from the average. Over the monitoring period, the River Ridge feedlot experienced an average temperature of 4.1°C overall and 11.1°C for April to October (Appendix A). Long-term data from Eston shows an annual average temperature of 3.1°C and 12.1°C for April to October.

Total potential evaporation for the feedlot for Sept. and Oct. 2003 was 149 mm (Table 4.11), and that of Apr. to Aug. 2004 was 599 mm. Standardized reference (ETsz) potential evapotranspiration values were calculated from available meteorological station data from the feedlot for the monitoring period. Hargreaves potential evapotranspiration was calculated from supplemental data (91 days) from Kindersley meteorological station for the monitoring period.

4.4.7 Determination of Change in Soil (ΔS) and Manure Moisture Storage (ΔMP)

The change in soil moisture storage in the top 0.6 m of the scraped soil surface (Figure 4.11) over the monitoring period for the inactive feedlot was calculated to be 40 mm, and for the summer months alone, the largest change in soil moisture storage in the top 0.6 m of the scraped soil surface for the inactive feedlot was calculated to be 14 mm. In addition, 14 mm of moisture was estimated to have infiltrated into the soil from snowmelt.

The dry manure pack (including the granular and compacted manure layers) was assumed to have a negligible increase in volumetric moisture content over the fall and spring/summer months, based on visual observation. What was left of wet manure pack had an increase of 9 mm over the spring and summer months and a negligible increase during the fall months. In addition, 33 mm of moisture was estimated to have infiltrated into the manure pack from snowmelt.

4.4.8 Determination of Drainage (D)

Drainage due to excess moisture (greater than field capacity) in the soil profile was determined to be zero for that of an inactive feedlot with a manure pack and a scraped soil surface. Since the volumetric moisture contents of the soil from 0 to 0.6 m depths over the monitoring year were less than field capacity (0.24 m^3/m^3, Table 4.6), minimal drainage would have occurred below 0.6 m. In addition, the change in soil moisture content in the 0.6 to 1.2 m depths over the monitoring period was determined to be negligible (Table 4.11), thus confirming the measurement of minimal drainage due to excess moisture below a depth of 0.6 m.

Also, literature has shown drainage below active feedlots to be between 2 and 6 mm per year (Maule and Fonstad 2002). Since the River Ridge feedlot was inactive, the drainage would likely be even less than this value, which confirms the lack of drainage from excess moisture measured in the soil below 0.6 m.

4.4.9 Determination of Runoff (R)

The weir was in operation for only a short time (July 1st to Aug 31st, 2004) throughout which there were no measured runoff events. In addition, there was also no runoff observed during visits to the feedlot site, nor any evidence of runoff events from pooled water in the storage pond.

During the period that the weir was operational, the maximum rainfall intensity experienced at the feedlot was 5.5 mm/h (from a 30 min event of 2.8 mm, Figure 4.8). There were five (24 h) rainfall events of greater than 10 mm/day, of which the largest was 19.3 mm received on August 7th, 2004 (Figure 4.6), which fell through the h of 8 am and midnight. The largest 30 min rainfall event experienced on this day was 0.88 mm (Figure 4.8) at 11 am and 6 pm.

The rainfall simulator tests (at rainfall rates between 34 and 39 mm/h) conducted on the manure pack took at least 2 hrs (and in one case 8 h) to achieve runoff. This was due to the dry state of the manure pack, which absorbed much of the rainfall. Rainfall simulator tests on the scraped soil surface (compacted manure layer was chipped away) at rainfall rates between 36 and 68 mm/h resulted in runoff occurring within one to six min.

4.4.9.1 Runoff from Snowmelt

The snowpack at the feedlot was very thin (depth was not measured) and a site visit during spring melt revealed no runoff from the pens into the storage ponds. Analysis of Kindersley data (Table 4.7) for the monitoring period showed a snowfall water equivalent of 33 mm, all of which was assumed to infiltrate into the manure pack, based on the initial and saturated volumetric moisture content of the granular layer of the dry manure pack (Table 4.5).

For a scraped soil surface with an initial moisture content of 0.21 m^3/m^3 for 0-50 mm soil depth, (Table 4.5) and a saturated volumetric moisture content of 0.32 m^3/m^3 (for 0-50 mm soil depth, Table 4.5) and a snowfall water equivalent of 33 mm (from Kindersley, Table 4.7), 13.7 mm will infiltrate into the surface soil (from Equation 2.7). Thus, by difference, runoff will total 19.3 mm.

4.4.9.2 Predicted Runoff from the Scraped Soil Surface and Manure Pack

Given the incomplete data set by the weir, two models (Green-Ampt model and USDA rainfall-runoff) were used to determine whether or not runoff might have occurred from the greatest 24 h rainfall events (25.5 and 19.3 mm, Figure 4.6) and the highest 30 min rainfalls (4.5 and 4.1 mm, Figure 4.8).

As discussed in Section 4.3.4, the USDA SCS model was used in the water balance. Thus, a total of 28.9 mm of runoff would be produced on a scraped soil surface for rainfall events experienced at the feedlot.

Both runoff models (Green-Ampt and USDA) predicted no runoff from the dry manure pack for the precipitation events experienced during the monitoring year at the River Ridge feedlot. In regards to the Green-Ampt model, the lack of runoff is due to the fact that the 30 min rainfall intensities experienced at the River Ridge feedlot were less than the infiltration rate of the manure pack (Table 4.12). The USDA SCS model also predicted a lack of runoff at the feedlot from the dry manure pack. Considering that there were no rainfall events greater than the minimum 24 h rainfall required to produce runoff during the monitoring year (either when the weir was operational or not), no runoff would be produced.

4.4.10 Determination of Actual Evaporation (AE)

For the water balance of both a manured and scraped soil surface at the River Ridge feedlot, drainage was measured and actual evaporation was calculated by difference (Equation 4.3). This method is generally accurate, as determined by Krentos et al. (1975) and Freeze and Cherry (1979), especially on the prairies where drainage values are quite low. Gee and Hillel (1988) stated that precipitation measurements are hardly ever more precise than ±5%, which introduces a measure of uncertainty into calculated parameters based on precipitation measurements.

The evaporation values calculated by difference in the water balance at the River Ridge feedlot for the spring and summer months were 183 mm for a scraped soil surface (from 252 mm precipitation – 40 mm change in soil moisture storage – 29 mm runoff) and 239 mm for a manure pack (from 252 mm precipitation – 9 mm change in manure pack moisture storage). This is reasonable because the feedlot site had no cattle adding moisture, plus the fact that there were few wet periods where the rainfall would have a chance to saturate the manure pack and create runoff. Thus, it would be likely that the precipitation would be stored in the manure pack and evaporate with time.

4.4.11 Uncertainties

There were several problems and difficulties encountered during the monitoring year that may have caused some uncertainty in relation to the measured and calculated values used in the water balance. Spatial variability, limited instrumentation at the feedlot, instrumentation problems, and difficulties in taking measurements on a regular basis because of the distance between Saskatoon and the feedlot site, may have caused a degree of error in several of the parameters used in the overall water balance of the feedlot.

For example, the soil and manure moisture storage measured during the fall, spring, and summer months could have some uncertainty associated with them. Disturbed samples of both the manure pack, as well as the scraped soil surface were taken from three different locations on each sampling date, and the calculated volumetric moisture content of the samples was based on an assumed bulk density (measured earlier in the year from undisturbed soil and manure samples). In addition, the majority of samples were only taken during the summer and fall of 2004.

Due to the uncertainties described above, the degree of error in the change in soil and manure pack moisture storage could be quite high. Since three different sampling locations were used, the overall change in moisture storage for the top 200 mm of the wet manure pack could vary from a 0.06 m^3/m^3 decrease to a 0.32 m^3/m^3 increase. This translated to a decrease of 12 mm to an increase of 64 mm of water. The change in moisture storage in the 200-400 mm depth of the manure pack ranged from a 22 mm decrease to 76 mm increase. The variation for the soil beneath the manure pack at 0-200 mm depth ranged from a 20 mm decrease to a 22 mm increase, that of the 200-400 mm depth varied from a 6 mm decrease to a 36 mm increase, and the 400-600 mm depth ranged from a 12 mm decrease to a 24 mm increase. The scraped soil surface measurements varied from a 10 mm decrease to a 22 mm increase for the 0-200 mm depth, a 4 mm decrease to a 12 mm increase for the 200-400 mm depth, and a 20 mm decrease to a 20 mm increase for the 400-600 mm depth.

Overall, the change in manure pack moisture storage could range from a 8.5 mm loss to a 35 mm gain of water based on the proportional coverage of the wet manure pack in the pens (25%, Table 4.10). The change in soil moisture storage beneath the manure pack could vary from a 38 mm loss to an 82 mm gain of water, and similarly, the change in soil moisture storage beneath the scraped soil surface could range from a 34 mm loss to a 54 mm gain.

A Kindersley snow water equivalent value of 33 mm was used in the water balance and this precipitation was assumed to have distributed itself evenly over the feedlot pen surface. In reality, this winter precipitation could have accumulated in excess amounts in drifts in certain areas of the pen, was prevented from accumulating by fences that surrounded the pens, or was lost through sublimation. As a result, the runoff and infiltration from snowmelt into/from the scraped soil surface and manure pack at the feedlot could vary by as much as ±50%. If only half as much snow was received at the River Ridge feedlot as compared to Kindersley, then only 16.5 mm of water would be available to infiltrate or run off during the winter. Alternately, if excess moisture accumulated in the pens, up to 50 mm of water could infiltrate or become runoff.

The infiltration equation for snowmelt by Gray et al. (1985) was developed for agricultural soils, not feedlot surfaces. As a result, this equation likely overestimated the amount of infiltration, and thus the soil and manure pack moisture storage, that occurred at the River Ridge feedlot. For the scraped soil surface, snowmelt infiltration was estimated to be 14 mm and for the manure pack, 33 mm. If all or part of the snowmelt sublimated or became runoff instead of infiltrating into the soil or manure pack, less moisture would have been available to infiltrate into the manure pack and scraped soil surfaces and the change in moisture storage could be in error by up to ±50%. If half of the snowmelt sublimated or became runoff instead of infiltrating into the soil or manure surface, only 7 mm of water would have infiltrated into the scraped soil surface and only 16.5 mm of water would have infiltrated into the manure pack.

As stated above, if half of the snowmelt became runoff instead of infiltrating into the soil or manure surface, an additional 7 mm of water would run off from the scraped soil surface and 16.5 mm runoff would be created from the manure pack. This amount of runoff from the manure pack is not likely, though, as little to no runoff was observed from the manure pack at the River Ridge feedlot, both with the weir, as well as the rainfall simulator trials.

The degree of error in predicted runoff from the USDA SCS model could have underestimated runoff from the scraped soil surface by as much as 36 mm, considering that the model did not take site-specific conditions into account, as well as the fact that there were no reference curve numbers developed for a scraped soil surface at a feedlot. In addition, the scraped soil surface had a relatively low saturated hydraulic conductivity of 5.1 x 10^{-6} cm/s (Table 4.3), indicating that a majority of incident rainfall would become runoff. Using a curve number for the scraped soil surface of 95 instead of 90 (as used in the water balance), the predicted runoff would increase to 65 mm. The higher curve numbers are in relation to studies by Miller et al. (2003) and Kizil and Lindley (2001), who found curve numbers of 92 to 96 for particularly wet conditions at active feedlots in North America. These numbers can then be related well to a scraped soil surface, where most of the incident rainfall would become runoff.

The predicted lack of runoff from the manure pack with the USDA SCS and Green-Ampt runoff models is likely accurate, as both models had good agreement. In addition, both the rainfall simulations and the weir installed at the feedlot did not measure any runoff at all from the manure pack during the monitoring period, indicating an accurate estimation of runoff from the manure pack surface.

Negligible drainage was determined based on limited measurements taken by the TDR probes installed at the site, which indicated that there was no excess moisture draining below a depth of 1.2 m. Other literature measured drainage to be close to 6 mm for active feedlots within the province. As a result, the water balance could underestimate drainage for both the scraped soil and manure pack by up to 6 mm.

Based on the inaccuracies of the other measured parameters in the water balance, the actual evaporation in the water balance could be underestimated by up to 52 mm or overestimated by 145 mm for the manure pack surface. For the scraped soil surface, the actual evaporation could be underestimated by up to 35 mm or overestimated by up to 87 mm.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The soil and manure pack water balance of an inactive feedlot during the monitoring year of September 1st, 2003 to August 31st, 2004 was considered. Although the initial intention of the study was focused upon an active feedlot, cattle were removed from the pens in July 2003. Therefore, the year of analysis was conducted on an inactive feedlot. The water balance of a scraped soil surface was also performed, since manure is usually scraped from the pen surface and spread on surrounding agricultural land once a year, leaving the bare surface soil exposed.

The meteorological station at the River Ridge feedlot was not operational for parts of the monitoring period, so rainfall and temperature data from Kindersley were used to supplement the missing feedlot data (91 days of the warm season). For the monitoring year, 313 mm of precipitation was received at the feedlot, but only 84 mm of that total was received before June 2004. Winter precipitation was very low (33 mm) and there was no observed runoff from it. The greatest 24 hour rainfall event experienced at the feedlot during the monitoring period was 25.5 mm on June 6th, 2004 and the highest 30 minute intensity was 4.5 mm, received on June 14th, 2004. Three wet periods also occurred from June 6th to 16th, 2004 (90 mm rainfall), July 1st to 12th, 2004 (44 mm) and July 26th to August 8th, 2004 (56 mm).

Using measured soil and manure properties, such as volumetric moisture content, the change in soil and manure pack moisture content over the monitoring period were determined. The manure pack (comprising 100% of the feedlot surface) in the feedlot consisted of the following three types of manure: the dry manure pack (60% of the total area made up of the granular and compacted manure layers together), the compacted manure layer (15%) and the remainder of the wet manure pack (25%). Taking each manure layer into account, the manure pack at the River Ridge feedlot was able to absorb 40 mm of water over the monitoring period, including that which infiltrated from snowmelt. Based on uncertainties in the estimated and measured values, though, the amount of water absorbed by the manure pack could be as low as 8 mm or as high as 85 mm.

For the scraped soil surface, the change in soil moisture content of the top 0.60 m of the soil was determined to be a 40 mm gain, with a degree of error in measurements ranging from a 34 mm loss to a 54 mm gain. For the summer months alone, the change in soil moisture was determined to be 24 mm, with the same degree of error. In addition, 14 mm of moisture was calculated to have infiltrated into the soil from snowmelt, but based on uncertainties in the calculated values, infiltration from snowmelt could range from 7 mm to 21 mm.

Drainage from excess moisture (greater than field capacity) movement below 0.6 m was determined to be negligible at the River Ridge feedlot. Current literature also supports this conclusion, with an average annual measurement of 2 to 6 mm of drainage occurring at an active feedlot in the province.

Runoff collection system weirs in operation for part of the summer (July and August, 2004) recorded no runoff. The largest 24 hour precipitation experienced while the weir was in operation was 19.3 mm on August 7th, 2004, and the greatest 30 minute intensity was 2.8 mm, received on August 5th, 2004. In addition, rainfall simulations conducted on the manure pack at rainfall rates between 34 and 39 mm/hr produced runoff only after about 2 hours (and in one case, over 8 hours). This was due to the dry state of the manure pack (antecedent moisture contents of 0.01 m^3/m^3 for the granular manure layer and 0.25 m^3/m^3 for the compacted manure layer), which absorbed most of the rainfall.

Steady state infiltration rates of the manure pack were determined to be 5.5×10^{-3} cm/s (from double ring infiltrometer measurements), 6.3×10^{-6} cm/s (from laboratory measurements) and 8.1×10^{-4} cm/s (from rainfall simulator measurements). The laboratory measurements of saturated hydraulic conductivity were used in runoff calculations, due to the fact that the field double ring infiltrometer and rainfall simulator trials had numerous errors associated with them.

Rainfall simulator tests on the scraped soil surface at rainfall rates between 36 and 68 mm/hr resulted in runoff occurring within one to six minutes. The rainfall simulator measured steady-state infiltration rates of 4.7×10^{-4} cm/s for the scraped soil surface, while the laboratory saturated hydraulic conductivity measurements showed an infiltration rate of 5.1×10^{-6} cm/s.

The Green-Ampt runoff equation, USDA SCS runoff model, and snowmelt runoff equation (Gray et al. 1985) were used to predict runoff from both the manure pack, as well as the scraped soil surface. Using manure and soil hydraulic parameters determined in the laboratory and the field (through rainfall simulations), as well as incorporating the greatest 24 hour rainfall amounts and 30 minute intensities experienced at the feedlot, the USDA SCS model found that 29 mm of runoff would occur from the scraped soil surface.

In contrast, the Green-Ampt model predicted no runoff from the scraped soil surface for the same conditions, which was considered more accurate because measured soil hydraulic properties were used in the model. The estimate from the USDA SCS runoff model was used in the water balance calculation, though, as it is the more standard model used to estimate runoff from feedlots. An estimate of runoff was also made for the winter precipitation received on the scraped soil surface, of which 19 mm would become runoff.

For the dry manure pack at the River Ridge feedlot, no runoff was predicted using all three runoff models, which corresponded well to the lack of runoff measured both from the weir and rainfall simulations.

The following water balance components were then determined for the one year period of Sept.1st, 2003 to Aug. 31st, 2004 (actual evaporation was calculated by difference method from the other water balance parameters):

- For the scraped soil surfaces in feedlot pens:
    - total precipitation: 313 mm gain (including 33 mm from snow)
    - change in soil moisture to 0.60 m: 54 mm gain
    - probable runoff: 48 mm loss
    - probable drainage: 0 mm
    - evaporation: 211 mm loss
- For the manure pack in feedlot pens:
    - total precipitation: 313 mm gain (including 33 mm from snow)
    - change in underlying soil moisture to 0.60 m depth: 0 mm
    - change in manure pack moisture content: 42 mm gain
    - probable runoff: 0 mm
    - probable drainage: 0 mm
    - evaporation: 271 mm loss

This water balance has great relevance in relation to the intensive livestock industry because it is important to help assess the potential for contamination in water pathways, such as drainage beneath the feedlot floor and surface runoff. The water balance has shown that based on the measured moisture content of the soil, there is no excess moisture draining below 0.6 m depth, thus preventing any contaminant outflow from reaching the groundwater. In addition, it is evident that little to no runoff will occur from the manured surface of an inactive feedlot, thereby preventing contaminants from entering surface water bodies.

Finally, it is apparent from the completion of the water balance that the scraped soil surface produces more runoff much sooner than that of the manured pen surface. As a result, it is important for producers to manage the scraped soil surface carefully to ensure that runoff and subsequent environmental impact is minimized.

5.2 Recommendations

It would be beneficial to incorporate the following recommendations into further study of a water balance of a feedlot pen in Saskatchewan:

- Perform a daily water balance of an active feedlot pen, as the moisture contents and measured runoff would be more appropriate for a typical feedlot scenario in the province.
- Validate both the USDA SCS and Green-Ampt models at an active feedlot with a weir runoff collection system that was in place and collecting data over an entire year.
- Install a water meter at the drinking bowls at an active feedlot to determine the amount of water that the cattle are consuming. Current literature could then be used to determine how much moisture the cattle excrete onto the pen floor.
- Conduct rainfall simulations on the wet manure pack at an active feedlot in order to determine the amount of runoff from a manured surface. It is extremely important to ensure that the plot barrier plates are pushed all the way through the manure pack into the underlying soil to ensure the prevention of lateral flow through the manure pack itself while the tests are being conducted.
- Conduct double ring infiltrometer measurements at an active feedlot over a several week period to measure the hydraulic conductivity of a wet manure pack and bare soil surface. It is extremely important to leave the ring infiltrometers in

place for several weeks to get a true measure of the steady-state infiltration rate of the manure pack and scraped soil surface. It is also extremely important to ensure that the rings are pushed all the way through the manure pack into the underlying soil to ensure the prevention of lateral flow through the manure pack itself while the tests are being conducted.

- Take disturbed samples of the top 600 mm of soil beneath the manure pack, as well as the scraped soil surface every month throughout the monitoring period.
- Take full undisturbed auger core samples from 0 to 1.2 m each season (fall, spring, and summer) with a hydraulic punch truck. It is also extremely important to get cores from the start and end of the monitoring period in order to determine an overall change in moisture content. These cores can then be cut into 50 mm lengths and the change in moisture content over the monitoring period and saturated hydraulic conductivity can be determined for each 50 mm soil depth.
- Take depth measurements and undisturbed samples of the wet manure pack (to depth) every four weeks over the monitoring period to determine the change in moisture of manure pack over the monitoring period.
- Use a tripod style rainfall simulator for rainfall simulations on the manure pack with a separate "tee-pee" style cover for protection from the elements.

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Appendix A – Calculation of Potential Evapotranspiration

Table A.1. Comparison of missing feedlot rainfall data and Kindersley and Eston long-term rainfall data (mm rainfall).

	Kindersley 1971-00	Eston 1971-00	Feedlot 2003-04	Kindersley Supplement 2003-04	Feedlot* 2003-04	# days supplement
Sept.	26.3	20.3	21.2	0.0	21.2	3 (0)
Oct.	13.5	11.0	3.1	4.4 (3.9)	7.0	26 (4)
Nov.	12.2	11.1	1.5	0.0	1.5	0 (0)
Dec.	14.7	14.6	NA	2.0	2.0	24 (4)
Jan.	10.9	13.0	NA	19.4	19.4	31 (13)
Feb.	6.8	9.5	NA	3.6	3.6	29 (4)
Mar.	14.0	14.8	0.1	7.6	7.7	28 (4)
Apr.	21.7	19.5	0.3	4.2 (3.7)	4.0	18 (2)
May	45.2	37.8	NA	19.6 (17.2)	17.2	20 (7)
Jun.	63.2	53.2	96.9	0.0	96.9	0 (0)
July	55.0	53.1	62.0	0.0	62.0	0 (0)
Aug.	42.7	39.3	49.9	25.0 (21.9)	71.8	24 (6)
Total warm	267.6	234.2	233.4	53.2 (46.6)	**280.1**	91 (19)
Total	326.2	297.2	235.0	85.8	314.3	203

Total warm: Total precipitation received through the months of Apr. to Oct., NA: data is not available, Feedlot*: precipitation including both feedlot and Kindersley supplement data, Kindersley supplement: amount of rainfall (mm) that was added to incomplete feedlot data (numbers in brackets are the corrected precipitation values for the feedlot – correction factor of 0.88 for rainfall events at Kindersley for warm season), # days supplement: number of days in the month feedlot climate station was not operating and had to be supplemented from Kindersley (numbers in brackets are the number of days in which precipitation occurred). Environment Canada 2004 supplied long term and hydrological year data for Kindersley. The meteorological station at the feedlot site supplied the feedlot hydrological year data.

As a result of the differences in long-term rainfall amounts between Eston and Kindersley during the warm season, each day of supplemental rainfall data from Kindersley for the monitoring period was corrected by a factor of 0.88 (from warm season data of 234.2 mm/267.6 mm, Table A.1). No winter precipitation was measured at the River Ridge feedlot due to the lack of proper instrumentation at the feedlot.

A comparison of available Kindersley and River Ridge feedlot meteorological data for the warm months of the monitoring year might be more appropriate, as the feedlot is further south than Eston and would likely experience less precipitation than that recorded by the meteorological station at Eston. Upon comparison of available warm season rainfall between Kindersley and the River Ridge feedlot (from Apr.1, 2003 to Oct. 1, 2003), each day of supplemental data from Kindersley for the monitoring period would have to be corrected by a factor of 0.94 (from 151 mm/161 mm). This comparison was not used, though, as the possibility of large rainfall events from one set of warm season precipitation measurements might distort the monthly averages for precipitation at each site.

Table A.2. Comparison of missing feedlot temperature data, Eston data, and Kindersley temperature data (°C).

	Kindersley 1971-00	Eston 1971-00	Kindersley 2003-04	Feedlot 2003-04	Feedlot* 2003-04	# days supplement
Sept.	11.4	11.4	11.3 (12.4)	12.9	12.9	3
Oct.	4.4	4.9	6.8 (7.5)	-1.1	-0.1	26
Nov.	-6.2	-5.6	-8.8	-8.6	-8.6	0
Dec.	-11.9	-12.5	-8.4	-4.9	-4.9	24
Jan.	-14.5	-14.3	-16.8	NA	-16.8	31
Feb.	-11.4	-11.5	-8.2	NA	-8.2	29
Mar.	-3.7	-4.0	-0.8	10.0	10.0	28
Apr.	5.0	4.8	5.5 (6.1)	6.8	6.8	18
May	11.3	11.7	8.7 (9.6)	8.1	8.3	20
Jun.	15.7	16.2	13.5 (14.9)	14.5	14.5	0
July	17.8	18.1	17.6 (19.4)	18.8	18.8	0
Aug.	17.3	17.4	14.8 (16.3)	16.2	16.2	24
Avg. warm	11.8	12.1	11.2 (12.3)	NA	11.1	91
Avg.	2.9	3.1	2.9	NA	4.1	203

Avg. warm: average temperatures for the months of Apr. to Oct., NA: data not available, numbers in brackets are Kindersley measured temperatures corrected by a factor of 1.1 for use as supplement for feedlot, Feedlot*: temperatures including both feedlot and Kindersley supplement data, # days supplement: number of days in the month feedlot climate station was not operating and had to be supplemented from Kindersley. Environment Canada 2004 supplied long term and hydrological year data for Kindersley. The meteorological station at the feedlot site supplied the feedlot hydrological year data.

Comparison of long-term temperature data collected at Eston (warm season period of Apr. to Oct.) to long-term data for Kindersley for the same period found that Eston was 0.3°C warmer (11.8°C for Kindersley vs. 12.1°C for Eston). For 2003-04, Kindersley warm season was 0.6°C cooler than that of the long-term average (11.2°C). As a result of the differences in long-term temperatures between Eston and Kindersley during the warm season, each day of supplemental temperature data from Kindersley for the monitoring period should be corrected by a factor of 1.03 (from 12.1°C/11.8°C, Table A.2). This correction was not used, though, as a comparison of available Kindersley and feedlot meteorological data would be more appropriate because the River Ridge feedlot is further south than Eston and would likely experience warmer temperatures than that recorded by the meteorological station at Eston.

Upon comparison of available warm season temperatures between Kindersley and the River Ridge feedlot (from Apr.1, 2003 to Oct. 1, 2003), each day of supplemental temperature data from Kindersley for the monitoring period was corrected by a factor of 1.1 (from 15.1ºC/13.8ºC). Winter temperature values for the River Ridge feedlot were not corrected with Kindersley values due to the fact that only warm season temperatures were used to correct the feedlot temperature values.

Table A.3 presents the potential evapotranspiration for the monitoring period, which was estimated to be 748 mm.

Table A.3. Summary of calculated potential evapotranspiration values for the feedlot and Kindersley (September 2003 to August 2004).

Month	Hargreaves Kindersley PET (mm)	Hargreaves feedlot PET (mm)	ETsz feedlot PET (mm)	Total feedlot PET (mm)	# days supplement
Sept.	10.6	81.4	91.7	102.3	3
Oct.	46.8	NA	NA	46.8	26
April	87.9	NA	NA	87.9	18
May	117.5	NA	NA	117.5	20
June	NA	138.7	129.5	129.5	0
July	NA	167.6	147.4	147.4	0
Aug.	96.7	23.4	19.5	116.2	24
Total	360	411	388	748	91

Potential evapotranspiration values do not include winter months Nov thru March, as there is no evapotranspiration when the temperature is below 0°C. Total feedlot PET: includes ETsz feedlot PET plus the Hargreaves Kindersley PET.

Available meteorological station data from the River Ridge feedlot for April to October was used in the ASCE standardized reference evapotranspiration equation (ETsz from ASCE 2002, Equation 3.9). Kindersley meteorological station temperature data for the same time period (Environment Canada 2004) was used to supplement the missing feedlot data (91 days for the warm season) in calculating the potential evapotranspiration by the Hargreaves (ETh from Hargreaves 1994, Equation 3.10) daily method (based on air temperature and extraterrestrial solar radiation at the feedlot latitude). Since the feedlot is slightly warmer and drier than Kindersley, the data used from Kindersley was corrected based on the calculated temperature difference between feedlot and Kindersley data for the warm season of 2003-04 (Table A.2). This would allow a more accurate estimation of the potential evapotranspiration at the River Ridge feedlot.

A comparison of potential evapotranspiration values for the available feedlot data made with the Hargreaves and ETsz methods indicated agreement between the methods, as the Hargreaves equation overestimated potential evapotranspiration by 23 mm as compared to the ETsz method for the same data. Considering the total evapotranspiration amounts calculated by each method, 23 mm is a reasonable difference, as the total values are in the 400 mm range. In support of this finding, Droogers and Allen (2002) also noted good agreement between the ETh and ETsz methods.

In comparison to the potential evapotranspiration calculated by ETh and ETsz for the same days of the 2003-04 monitoring period, ETh seems to underestimate potential evapotranspiration for days of high windspeed. For example, on June 17th, 2004, a relatively high wind speed of 5.5 m/s (Appendix A-1) was measured at the feedlot, and the ETsz value was calculated to be 5.84 mm. In comparison, the ETh value was 3.74 mm, which is much lower than that calculated by the ETsz method. This is due to the fact that the Hargreaves equation does not take wind speed into account.

In contrast, ETh seems to overestimate potential evapotranspiration for days of lower net radiation. On June 30th, 2004, a relatively low net radiation measurement of 9.1 MJ/m^2 (Appendix A-1) was measured at the feedlot, and the ETsz value was calculated to be 2.56 mm. In comparison, the ETh value was 3.56 mm, which is much higher than that calculated by the ETsz method. This could be due to the fact that the Hargreaves potential evapotranspiration was calculated using extraterrestrial solar radiation equation given by Hargreaves (1994) for a specific latitude, while actual solar radiation data from the meteorological station at the feedlot was used in the Standardized Reference Equation calculations of potential evapotranspiration.

Appendix A-1

Date	Tmx	Tmax	Tmin	Tmin	King Tav	Eston Tav	RHmx	RHmn	RHav	windav	Rs	ppttot
	C	correct	C	correct	C	C	%	%	%	m/s	MJ/m2	mm
2-Jun-04	27.8	30.58	10.8	11.88	19.3	20.438	88.9	19.74	36.09	3.536	27.5	6.569
3-Jun-04	17.44	19.184	10.36	11.396	13.9	14.112	93.1	60.72	83.32	4.754	13.02	25.55
4-Jun-04	26.21	28.831	5.441	5.9851	15.826	11.564	95.2	27.76	75.01	5.526	17.01	1.022
5-Jun-04	16.33	17.963	1.773	1.9503	9.0515	10.071	93.7	30.29	59.8	1.322	27.41	
6-Jun-04	20.3	22.33	5.232	5.7552	12.766	13.768	84.2	31.54	54.85	2.823	28.11	
7-Jun-04	13.43	14.773	10.49	11.539	11.96	11.727	97	68.8	85.55	2.962	2.748	14.89
8-Jun-04	12.13	13.343	9.65	10.615	10.89	10.888	97.3	89.3	93.59	4.172	5.879	15.62
9-Jun-04	11.64	12.804	8.34	9.174	9.99	9.8202	93.3	76	84.86	6.011	11.65	2.044
10-Jun-04	15.99	17.589	7.58	8.338	11.785	11.233	94.2	57.35	78.5	2.581	19.45	
11-Jun-04	16.83	18.513	7.6	8.36	12.215	11.114	93	52.45	80.51	2.096	15.31	19.42
12-Jun-04	15.66	17.226	8.48	9.328	12.07	11.661	95.8	57.68	79.51	4.092	19.39	10.8
13-Jun-04	19.11	21.021	5.462	6.0082	12.286	12.024	92.1	46.72	75.11	4.327	23.6	0.146
14-Jun-04	15.17	16.687	2.872	3.1592	9.021	9.2346	91.8	29.5	58.9	3.184	24	
15-Jun-04	19.46	21.406	4.013	4.4143	11.737	13.099	79.7	24.31	46.31	1.35	30.48	
16-Jun-04	22.95	25.245	8.45	9.295	15.7	16.592	63.03	20.13	37.85	3.685	30.78	
17-Jun-04	18.82	20.702	12.02	13.222	15.42	15.968	65.59	32.7	46.29	5.507	25.66	
18-Jun-04	21.44	23.584	6.968	7.6648	14.204	14.946	80.6	29.39	56.06	2.371	23.08	0.584
19-Jun-04	22.74	25.014	9.24	10.164	15.99	14.996	81.5	21.98	54.09	3.702	22.95	0.292
20-Jun-04	17.7	19.47	6.018	6.6198	11.859	12.434	66.64	24.66	42.46	2.32	21.5	
21-Jun-04	21.75	23.925	1.655	1.8205	11.703	13.444	77.2	22.63	41.85	2.163	28.87	
22-Jun-04	22.87	25.157	3.619	3.9809	13.245	15.244	71.5	20.06	40.31	1.612	31.07	
23-Jun-04	22.27	24.497	8.16	8.976	15.215	16.061	73.7	24.8	47.44	2.25	25.66	
24-Jun-04	25.06	27.566	7.29	8.019	16.175	17.792	76.4	24.97	45.15	1.418	30.57	
25-Jun-04	27.66	30.426	10.09	11.099	18.875	20.373	68.62	19.1	39.99	1.712	30.19	
26-Jun-04	30.3	33.33	10.56	11.616	20.43	22.163	71.8	21.81	39.77	1.4	29.68	
27-Jun-04	28.22	31.042	12.95	14.245	20.585	21.375	78.5	31.96	51.48	2.726	20.77	
28-Jun-04	27.67	30.437	17.39	19.129	22.53	22.588	89	37.07	60.04	2.672	20.3	4.672
29-Jun-04	23.92	26.312	14.22	15.642	19.07	18.388	95.3	54.51	80.25	3.605	18.64	0.73
30-Jun-04	18.06	19.866	11.55	12.705	14.805	15.064	94.9	70.5	85.37	3.465	13.56	2.336

Appendix B - Eston and Kindersley total precipitation (mm)

Date	Corrected precipitation		Precipitation-PET
1-Jul-04	4.6715328	1.1161511	3.5553817
2-Jul-04	0.729927	2.5286989	1.7566098
3-Jul-04	2.3357664	4.7204727	0
4-Jul-04	13.430657	3.8493297	9.5813272
5-Jul-04	3.3576642	3.1340244	9.8049671
6-Jul-04	0.5839416	4.467777	5.9211316
7-Jul-04	6.2773723	5.2749254	6.9235786
8-Jul-04	6.2773723	5.3257387	7.8752121
9-Jul-04		4.780688	3.0945242
10-Jul-04		5.1444416	0
11-Jul-04	6.4233577	5.9623008	0.4610569
12-Jul-04	0.2919708	5.4057114	0
13-Jul-04		5.5174536	0
14-Jul-04		7.1922187	0
15-Jul-04		6.556271	0
16-Jul-04		6.4581704	0
17-Jul-04		5.869992	0
18-Jul-04		4.802467	0
19-Jul-04	0.2919708	4.1859417	0
20-Jul-04	3.3576642	4.4006358	0
21-Jul-04	1.0218978	6.343619	0
22-Jul-04	5.8394161	7.2497908	0
23-Jul-04		5.8981566	0
24-Jul-04		3.2487381	0
25-Jul-04		5.6696454	0
26-Jul-04	1.459854	4.190903	0
27-Jul-04	0.1459854	3.8507665	0
28-Jul-04		4.9094642	0
29-Jul-04		2.2731721	0
30-Jul-04	4.2335766	3.1526133	1.0809634
31-Jul-04	0.4379562	3.8819847	0
1-Aug-04	10.072993	3.328964	6.7440287
2-Aug-04	0.4379562	6.2879594	0.8940256
3-Aug-04	5.6934307	5.7070359	0.8804203
4-Aug-04	2.0437956	2.3948371	0.5293789
5-Aug-04	5.2554745	1.9259571	3.8588962
6-Aug-04	4.9635036	3.7768336	5.0455663
7-Aug-04	19.270073	2.5511977	21.764442
8-Aug-04	2.189781	2.0187352	21.935487
9-Aug-04		3.5393624	18.396125
10-Aug-04		4.6597892	13.736336
11-Aug-04		4.9406612	8.7956747
12-Aug-04		4.7746631	4.0210116
13-Aug-04		5.4012269	0
14-Aug-04		5.9272348	0
15-Aug-04		4.7228728	0
16-Aug-04		4.8223472	0
17-Aug-04		4.9347099	0
18-Aug-04		4.4633753	0
19-Aug-04		4.0823351	0
20-Aug-04		4.9487476	0
21-Aug-04	1.2	3.6311706	0
22-Aug-04	3.2	1.8584551	1.3415449
23-Aug-04	12.4	1.3653064	12.376238

24-Aug-04		2.448763	9.9274755
25-Aug-04		3.7421898	6.1852857
26-Aug-04		3.4546296	2.7306561
27-Aug-04	2.2	3.9549777	0.9756784
28-Aug-04		3.880105	0
29-Aug-04		3.5089275	0
30-Aug-04	5.8	2.7013328	3.0986672
31-Aug-04	0.2	4.4008746	0

Appendix C – Sensitivity analysis for scraped soil surface

Table C.1. Sensitivity analysis for time to start of runoff on scraped pen surface.

Ψ (cm)	Ks (cm/s)	i (mm/hr)	Md (m^3/m^3)	ts (min)
-30	5.1×10^{-6}	36	0.15	0.4
-30	5.1×10^{-6}	55	0.15	0.2
-30	5.1×10^{-6}	68	0.15	0.1
-15	5.1×10^{-6}	36	0.15	0.2
-15	5.1×10^{-6}	55	0.15	0.1
-15	5.1×10^{-6}	68	0.15	0.1
-45	5.1×10^{-6}	36	0.15	0.6
-45	5.1×10^{-6}	55	0.15	0.3
-45	5.1×10^{-6}	68	0.15	0.2
-30	8.5×10^{-5}	36	0.15	6.8
-30	**8.5×10^{-5}**	**55**	**0.15**	**2.8**
-30	8.5×10^{-5}	68	0.15	1.8
-15	8.5×10^{-5}	36	0.15	3.4
-15	8.5×10^{-5}	55	0.15	1.4
-15	8.5×10^{-5}	68	0.15	0.9
-45	8.5×10^{-5}	36	0.15	10.2
-45	8.5×10^{-5}	55	0.15	4.2
-45	8.5×10^{-5}	68	0.15	2.7
-30	4.7×10^{-4}	36	0.15	105
-30	4.7×10^{-4}	55	0.15	30.3
-30	4.7×10^{-4}	68	0.15	17.7
-15	4.7×10^{-4}	36	0.15	52.5
-15	4.7×10^{-4}	55	0.15	15.2
-15	4.7×10^{-4}	68	0.15	8.9
-45	4.7×10^{-4}	36	0.15	158
-45	4.7×10^{-4}	55	0.15	45.5
-45	4.7×10^{-4}	68	0.15	26.6
-30	5.1×10^{-6}	36	0.10	0.3
-30	8.5×10^{-5}	36	0.10	4.5
-30	4.7×10^{-4}	36	0.10	70
-30	5.1×10^{-6}	55	0.10	0.1
-30	8.5×10^{-5}	55	0.10	1.9
-30	4.7×10^{-4}	55	0.10	20.2
-30	5.1×10^{-6}	68	0.10	0.1
-30	8.5×10^{-5}	68	0.10	1.2
-30	4.7×10^{-4}	68	0.10	11.8
-30	5.1×10^{-6}	36	0.20	0.6
-30	8.5×10^{-5}	36	0.20	9.1
-30	4.7×10^{-4}	36	0.20	140

-30	5.1×10^{-6}	55	0.20	0.2
-30	8.5×10^{-5}	55	0.20	3.8
-30	4.7×10^{-4}	55	0.20	40.4
-30	5.1×10^{-6}	68	0.20	0.2
-30	8.5×10^{-5}	68	0.20	2.4
-30	4.7×10^{-4}	68	0.20	23.7
-15	8.5×10^{-5}	36	0.10	2.3
-15	8.5×10^{-5}	55	0.10	0.9
-15	8.5×10^{-5}	68	0.10	0.6
-45	8.5×10^{-5}	36	0.20	4.5
-45	8.5×10^{-5}	55	0.20	1.9
-45	8.5×10^{-5}	68	0.20	1.2
	5.1×10^{-6}	5.5	0.15	12.3

Ψ: tension at the wetting front, Ks: saturated hydraulic conductivity, i: rainfall rate, Md: moisture deficit, ts: time to start of runoff.

Appendix D – Green-Ampt Runoff for Greatest Rainfall Intensities

If the greatest 30 minute intensities (and their associated storms) are used in the Green-Ampt model for a scraped soil surface (4.5 mm from June 14th, 4.1 mm from July 1st, and 2.8 mm from Aug. 5th, Figure 4.8), runoff will still not result. June 14th was also within a wet period (59 mm rainfall had been received since June 6th), so the moisture deficit was likely less than the 0.15 m^3/m^3 used in the model for rainfall simulations. Since the highest moisture content in the top 200 mm of the soil was 0.27 m^3/m^3 over the monitoring year (Figure 4.11) at the River Ridge feedlot, a moisture deficit of 0.08 m^3/m^3 was used in the Green-Ampt model for this wet period.

With a moisture deficit of 0.08 m^3/m^3 (as estimated above for the wet period at the feedlot), for the first 30 minutes of rainfall with an intensity greater than the saturated hydraulic conductivity of 8.5 x 10^{-5} cm/s (2.6 mm converted to 5.3 mm/hr), runoff would not start for over 354 minutes (Table 4.16).

Table 4.16. Time to runoff on a scraped soil surface for rainfall rates experienced at the feedlot on June 14th, 2004.

Parameter	Change with time during storm event				
Ks (cm/s)	8.5 x 10^{-5}	8.5 x 10^{-5}	8.5 x 10^{-5}	8.5 x 10^{-5}	8.5 x 10^{-5}
θs (m^3/m^3)	0.35	0.35	0.35	0.35	0.35
θi (m^3/m^3)	0.27	0.28	0.29	0.3	0.31
Md (m^3/m^3)	0.08	0.07	0.06	0.05	0.04
Ψ (cm)	-30	-30	-30	-30	-30
i (mm/hr)	5.3	8.8	9.1	7.9	4.1
Fs (cm)	1.5	0.6	0.5	0.5	1.1
ts (min)	354.4	74.1	58.4	69.7	478.9

In this time, though, the rainfall rate had increased to 8.8 mm/hr (for 30-60 minutes) and an estimated increase in moisture content of 0.01 m^3/m^3 occurred. This increase in moisture content after 30 minutes of rainfall was calculated by adding the amount of water that infiltrated in 30 minutes to the initial moisture content of the top 50 mm of soil. Runoff was not created in the 30-60 minute interval (runoff would start just after 74 minutes) and the rainfall rate increased after 60 minutes to 0.91 cm/hr for the 60-90 minute interval (again with an increase of 0.01 m^3/m^3 in moisture content), which would not create runoff for another 58 minutes. As the subsequent rainfall intensities decrease after 90 minutes, the entire rainfall event would not produce any runoff.

July 1st was at the start of a wet period, so the moisture deficit at the start of the July 1st storm was likely similar to that of the rainfall simulations (0.15 m^3/m^3). If wetter conditions are assumed because the first half of June is wet, but the second half is dry (Figure 4.6), a worst-case moisture deficit of 0.08 m^3/m^3 would likely result (Figure 4.11). For the first 30 minutes of rainfall (4.1 mm converted to 8.2 mm/hr), runoff would not start for over 101 minutes. In this time, the rainfall rate had decreased to 0.9 mm/hr (for 30-60 minutes). If runoff had not started in the first 30 minutes and the rainfall intensity decreased in the subsequent 30 minutes and kept decreasing with time, no runoff will be produced. In addition, in this case, the rainfall rate decreased after the first 30 minutes to less than the infiltration rate of the scraped soil surface.

While the weir was in operation, the largest 30 minute rainfall event at the feedlot totaled 2.8 mm (on August 5th, Figure 4.8). Aug. 5th was in the middle of the wet period (25 mm rainfall had been received), so the moisture deficit was likely less than 0.15 m^3/m^3 (correlated from the model for rainfall simulations). Since the highest moisture content in the top 200 mm of the soil was 0.27 m^3/m^3 over the monitoring year (Figure 4.11), a moisture deficit of 0.08 m^3/m^3 was used in the Green-Ampt model. For the first 30 minutes of rainfall (2.5 mm converted to 5.0 mm/hr), runoff would not start for over 432 minutes. In this time, the rainfall rate had increased to 0.55 cm/hr (for 30-60 minutes), but no runoff would be produced for 275 minutes at this intensity. The rest of the rainfall intensities in the storm did not exceed the saturated hydraulic conductivity of the scraped soil surface (8.5×10^{-5} cm/s), and therefore, would not produce any runoff.